

AD A091676

LEVEL ✓

AD _____

PREDICTABILITY OF BURN DEPTH:
DATA ANALYSIS AND MATHEMATICAL MODELING BASED
ON USAARL'S EXPERIMENTAL PORCINE BURN DATA

FINAL REPORT

BY

Francis S. Knox III, Ph.D.

June 1979



Supported by

U. S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Maryland 21701

Contract No. DAMD17-77-C-7004

LSU SCHOOL OF MEDICINE IN SHREVEPORT
Department of Physiology and Biophysics
Shreveport, Louisiana 71130

Approved for public release
distribution unlimited

The findings in this report are not to be construed as an official
Department of the Army position unless so designated by other
authorized documents.

8011 05 030

DOC FILE COPY

Final & pt. 1 Jul 15-21 81, 78

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 6	2. GOLY ACCESSION NO. AD-A091676	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Predictability of Burn Depth: Data Analysis and Mathematical Modeling Based on USAARL's Experimental Porcine Burn Data,		5. TYPE OF REPORT & PERIOD COVERED Final Report 1 July 1975 thru 9/30/78
7. AUTHOR(s) Francis S. Knox, III, Ph.D.		6. PERFORMING ORG. REPORT NUMBER 15 DAMD17-77-C-7004 DART 17-15-8-0257
9. PERFORMING ORGANIZATION NAME AND ADDRESS Louisiana State University Medical Center, School of Medicine in Shreveport, P. O. Box 33932, Shreveport, Louisiana 71130		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62773A (3E162773A819) 00.022 16 171701
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Medical Research and Development Command, Fort Detrick, Frederick, Maryland 21701		12. REPORT DATE 11 June 1979
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 104 140
16. DISTRIBUTION STATEMENT (of this Report)		15. SECURITY CLASS. (of this report) Unclassified
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) pig; porcine; burns (flame); mathematical model; simulated post-crash fire; thermally protective clothing		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the work accomplished during the contract period 1 July 1975 through 30 September 1978. The working hypothesis of this study was: given the output of physical thermal sensors and the actual burns experienced by pigs, it should be possible to develop a mathematical model which can convert the output of the sensors to predicted burn depths in reasonable agreement with the observed burn depths. The specific objectives accomplished are as follows: 1) the previously collected data base was reviewed for error both in coding and		

in content; 2) the biopsy specimens were re-read using a new set of standards so that corrections for thermally induced tissue shrinkage could be calculated; 3) graphical representations of the data contained in the revised data base were made as a help in understanding the relationships embodied in the data; 4) an empirical, multidiscriminant model was written which predicts either gross (clinical) grade or histopathologic grade given parameters such as heat flux, exposure time, skin temperature, and the like; 5) an analytical model was developed to circumvent the problems associated with the multidiscriminant model regarding the inability to use a flux-time profile; 6) optimization of the analytical model was accomplished using data in the data base, intraskin time-temperature profiles and such data as could be found in the literature, e.g. University of Rochester, Moritz and Henriques and Stoll, as performance criteria. Abstracts of 10 additional reports covering various aspects of the project in more detail and a listing of BRNSIM, the analytical model are appended. Conclusions and Recommendations include:

- 1) The USAARL Porcine Burn Data Base is ready for release.
- 2) Data handling and graphing programs are available to facilitate further study.
- 3) BRNSIM, which predicts burn depths over a wide range with reasonable accuracy, should be tested against the Aerotherm manikin model.
- 4) Skin cooling by blood and tissue water boiling should be further studied.
- 5) BRNSIM should be tested using Stoll's extensive human burn data base.

PREFACE

Research discussed in this report was accomplished between 1 July 1975 and 30 September 1978 by the author under USAARL Contract DABT01-75-C-0257 (1 July 1975 through 30 September 1976) and USAMRDC Contract No. DAMD17-77-C-7004 (1 October 1976 through 30 September 1978). The original data was collected at the U. S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama between June 1972 and January 1973.

In the data collection phase of this project the animals used were procured, maintained and used in accordance with the Animal Welfare Act of 1970 and AR 70-18. The investigators adhered to the "Guide for Laboratory Animal Facilities and Care", as promulgated by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences, National Research Council.

The vivarium of the United States Army Aeromedical Research Laboratory (USAARL) is fully accredited by the American Association for Accreditation of Laboratory Animal Care.

The author publicly extends his thanks to his colleagues Thomas L. Wachtel, M.D., George McCahan, D.V.M., and Stanley C. Knapp, M.D., to his consultants Charles Yuile, M.D., Daniel D. Reneau, Ph.D., George McCormick, M.D. and Pat Duffy, M.D., and his assistants Peter Sauermilch, B.S., Ransom Nockton, M.S. and Chester Ellis, M.S., and the staff of USAARL for their many and varied contributions.

Accession #	1
NTIS #	DAIR
DTIC #	1
Unannounced	1
Justification	1
By	1
Distribution	1
Availability Codes	1
Avail and/or Dist Special	1

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	10
1.1. Experimental Rationale	10
1.2. Data Collection	10
1.3. Analysis by IITRI	11
1.4. Working Hypothesis	11
1.5. Objectives	11
1.6. Summary	12
2.0 DATA BASE VALIDATION	13
2.1. Eliminate Keypunch/Transcription Errors	13
2.2. Re-Read Biopsy Material to Allow for Shrinkage Correction	13
2.3. Corrections to Original Data	16
2.3.1. Shutter Dynamics	16
2.3.2. Initial Skin Temperature	16
2.3.3. Hair Removal	16
2.4. Data Management Computer Programs	16
3.0 GRAPHIC PRESENTATION OF THE DATA BASE	18
4.0 EMPIRICAL MODEL	32
5.0 ANALYTICAL MODEL	32
6.0 SOLUTION OF MATHEMATICAL MODEL	35
7.0 THERMAL PROPERTIES OF SKIN	38
8.0 INTRASKIN TEMPERATURES	39
9.0 PREDICTIONS FROM SENSOR DATA	40

TABLE OF CONTENTS

	<u>Page</u>
10.0 COMPARISON WITH WEAVER AND STOLL (7)	62
11.0 UNANALYZED SENSOR DATA	62
12.0 DISCUSSION	68
13.0 CONCLUSIONS AND RECOMMENDATIONS	68
14.0 REFERENCES	70

LIST OF APPENDIXES

	<u>Page</u>
APPENDIX A: Bibliography - Thermal Project	72
APPENDIX B: Bibliography - Thermal Analysis Program: Abstracts of Reports and Papers in Preparation	76
APPENDIX C: BRNSIM 3 - Listing of the Interactive Analytical Model BRNSIM	83

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Schematic Diagram of Porcine Skin Showing Location of Measurements A through E Recorded for Each Biopsy Specimen	14
2	Gross Grade vs. Normalized Burn Depth	20
3	Gross Grade vs. Corrected Burn Depth	21
4	New Micro Grade vs. Normalized Burn Depth	22
5	New Micro Grade vs. Corrected Burn Depth	23
6	New Micro Grade vs. Total Flux	24
7	Gross Grade vs. Total Flux	25
8	Gross Grade vs. New Micro Grade	26
9	Log Exposure Time vs. Log Flux Parameterized by New Micro Grade 4	27
10	Log Exposure Time vs. Log Flux Parameterized by New Micro Grade 6	28
11	Log Exposure Time vs. Log Flux Parameterized by New Micro Grade 9	29
12	Normalized Burn Depth vs. Total Flux Parameterized by Exposure Time	30
13	Gridwork for Numerical Analysis	36
14	One Page Summary Report from a Simulation of the Exposure of Pig 294RF	41
15	Photographs of Intraskin Thermocouple Before and After Burn	42
16	Observed Temperature Profile #27 Overlaid on the Calculated Temperature Profile	43
17	Observed Temperature Profile #28 Overlaid on the Calculated Temperature Profile	44

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
18	Observed Temperature Profile #29 Overlayed on the Calculated Temperature Profile	45
19	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off	46
20	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #27	47
21	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #28	48
22	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #29	49
23	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On	50
24	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #27	51
25	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #28	52
26	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #29	53
27	Simulation of Pig 296RF in 8.2 Seconds at 2.36 cal/cm ² /sec	56
28	Temperature Plot of Simulation (Fig. 27) Showing Model Instability Due to Recalculation of Thermal Properties	57
29	Simulation Which Results in a Prompt Cooling of the Skin Following Shutter Closure when Recalculation of Thermal Properties is Inhibited	58

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
30	Simulation Which Results in a Prompt Cooling of the Skin Following Shutter Closure when Recalculation of Thermal Properties is Inhibited	59
31	Results of a Simulation of Aerotherm Thermoman Sensor in Contact with Fabric	61
32	Results of a Comparison of Predictions of BRNSIM (M12VB0120) with Weaver and Stoll's Measured Surface Temperature	64
33	Results of a Comparison of Predictions of BRNSIM (M12VB0120) with Weaver and Stoll's Measured Surface Temperature	65
34	Results of a Comparison of Predictions of BRNSIM (M12VB3745) in Which Blood Cooling Starts at 37 Seconds Postburn with Weaver and Stoll's Measured Surface Temperature	66
35	Results of a Comparison of Predictions of BRNSIM (M12VB3745) in Which Blood Cooling Starts at 37 Seconds Postburn with Weaver and Stoll's Measured Surface Temperature	67

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Histopathological and Burn Depth Grading Definitions	15
II	Regression Analysis of Pig Skin Temperatures	17
III	One Page Sample Listing of the Primary Data Base	19
IV	Results of Applying an Empirical Model to Predict Gross Burn Grade	33
V	Model Parameters Changeable Interactively	37
VI	Comparison of Burns Observed in Bioassay Test with Predictions of Model 3	54
VII	Effect of Normalized Depth in Reducing RMS Error in Data Summarized in Table VI	55
VIII	Summary of Twenty Simulations of Fabric Covered Sensors Comparing Predicted Depths with Both Normalized and Corrected Depths	60
IX	Effect of Normalized Depth in Reducing RMS Error in Sensor Data Summarized in Table VIII	63

1.0 INTRODUCTION

This is the final report of a data analysis and model development study based on information collected in USAARL's Thermal Analysis Program. (1, 2)

The overall technical objective was to provide managers with a clinically valid algorithm for evaluating thermally protective fabrics with potential for military use. The basic question which managers need answered is whether a particular fabric will, when exposed to an accurate simulation of a post-crash fire, reduce thermal transfer to clinically safe levels, and, if so, for how long? Colateral to this basic question is whether the fabric itself adds hazard by becoming a secondary thermal source. If a particular fabric becomes a secondary source, it is then important to know the degree to which it increases the hazard.

In order to answer these questions, a logical approach would be to expose fabrics to a controlled thermal source which accurately simulates a post-crash fire and to measure the thermal transfer through the fabrics with skin simulants or heat flux transducers. This approach, if carefully carried out, would provide accurate, reproducible engineering data on thermal transfer through the fabrics. However, it would not, by itself, provide clinically meaningful data. Calories per second transferred is not biologically significant information. What is significant is the resulting tissue damage. It is this thermally induced damage and not the heat transfer per se which incapacitates or kills the army aviator.

1.1 EXPERIMENTAL RATIONALE

The original Thermal Analysis Program (1, 2) was set up to determine the relationships which exist between thermal transfer and injury production. The experimental rationale was as follows: Heat flux transducers and the skin of pigs, as a human skin analog, were exposed to the same accurately simulated post-crash fire produced by a specially designed shuttered furnace burning JP-4 fuel (3). Both sensors and skin were exposed either bare, or while covered by layers of test fabric. Thus the sensors gave an accurate indication of heat flux as a function of time with direct exposure or as modified by fabric layers. The skin tissue samples gave a valid measurement of clinical damage.

1.2 DATA COLLECTION

From July, 1972 to January, 1973 a large body of experimental data was collected using the USAARL porcine bioassay technique (1, 2, 3) relating thermal flux and exposure time to burn depth. Physical thermal sensors were also exposed to the simulated post-crash fires in hopes of establishing a correlation between their output and the burns received by the pigs.

1.3 ANALYSIS BY IITRI

During the collection period and shortly thereafter, IIT Research Institute, under contract, analyzed the data that was being collected and developed a mathematical model for predicting burn injury (4) based on earlier work by Henriques (5), Stoll and Greene (6), Weaver and Stoll (7), Mehta and Wong (8) and Morse et al (9). IITRI's model could accept either a constant heat flux as an input parameter or a table of heat fluxes as would be generated from the heat flux sensor either in a laboratory test or as part of an instrumented manikin used in "fire pit" testing. But, during the data collection and model building, both IITRI and USAARL personnel observed that the data was noisy and that the model could be improved. There were also some items of data either not available during this period or not utilized by IITRI such as: 1) intraskin temperature recordings; 2) heat flux values derived from analog output of the heat flux sensors which had been recorded on FM magnetic tape; 3) burn depth readings which allowed for corrections to be made accounting for the shrinkage observed to occur in the more severely burned tissues; 4) additional measurements of tissue water and density.

1.4 WORKING HYPOTHESIS

The hypothesis of this study was: given the output of physical thermal sensors and the actual burns experienced by pigs, it should be possible to develop a mathematical model which can convert the output of the sensors to predicted burn depths in reasonable agreement with the observed burn depths. To the extent that this were possible, it would be reasonable to use such a physical thermal sensor and the mathematical model thus derived as part of a screening methodology for thermally protective fabrics.

1.5 OBJECTIVES

The specific objectives accomplished toward developing a clinically valid fabric screening method are as follows: 1) the previously collected data base was reviewed for error both in coding and in content; 2) the biopsy specimens were re-read using a new set of standards so that corrections for thermally induced tissue shrinkage could be calculated; 3) graphical representations of the data contained in the revised data base were made as a help in understanding the relationships embodied in the data; 4) an empirical, multi-discriminant, model was written which predicts either gross (clinical) grade or histopathologic grade given parameters such as heat flux, exposure time, skin temperature, and the like. However, since this model required either a constant input flux or the use of total flux, its use is limited, making the model incapable of using the thermal exposures experienced at the "fire pit" test facility of Natick labs; 5) an analytical model was developed to circumvent the problems associated with the multidiscriminate model regarding the inability to use a flux-time profile; 6) optimization of the analytical model was accomplished using data in the data base, intraskin time-temperature profiles and such data as could be found in the literature, e.g. University of Rochester, Moritz and Henriques and Stoll, as performance criteria.

1.6 SUMMARY

In summary then, the objectives were to validate the data base collected by the staff at USAARL, to look at the data in graphic presentation, to ascertain functional relationships and problems with the data and to develop, ultimately, a model which would take the output from heat flux sensors and accurately predict the burn depth which would have occurred had the sensor itself been replaced by living skin. The remainder of the report will deal with the work accomplished to meet each of these objectives taken in the order just presented.

2.0 DATA BASE VALIDATION

Data from the thermal project were recorded in three forms: 1) handwritten records, e.g. gross (clinical) grading sheets; 2) stripchart recordings of temperature, heat flux and shutter system state as a function of time; 3) analog voltages representing temperature and heat flux recorded on FM magnetic tape. At the start of this contract the written records had been coded on computer oriented record forms and key-punched on computer cards. These cards were read into data files which then became the data base. None of the data on FM magnetic tape had been utilized although it had been digitized and stored on digital magnetic tape as part of the contract performed by IITRI (4).

In order to form a data base containing pertinent information from all sources, which was reasonably free of error, the following tasks were accomplished.

2.1 ELIMINATE KEYPUNCH/TRANSCRIPTION ERRORS

The entire data base was read item by item and compared with the original data records (clinical grading forms, pathology reports, etc.). Errors were eliminated and those observations which did not match, e.g. a gross grade of 15 with a burn depth of 200 μ m, were further checked against the photographic records and biopsy material to resolve the mismatch.

2.2 RE-READ BIOPSY MATERIAL TO ALLOW FOR SHRINKAGE CORRECTION

It became apparent late in the data collection period (10) that biopsies from deep dermal burns showed a marked thermally induced shrinkage while more superficial burns showed some edema and swelling. The edema and swelling was slight, approximately 3-5%, and not as dramatic as seen in human burns (11). The shrinkage, on the other hand, was at least 40% and went as high as 216%. Clearly correction for such a large distortion of measured burn depth would enhance the chances of a model's ability to predict burn depth.

With this in mind, the entire set of more than 1600 biopsy slides was re-read using descriptive criteria as before (1) but adding several new depth measurements as shown in Figure 1. By recording both normal skin thickness, (A + B), and burned skin thickness, (E), as well as "depth of burn" C it was possible to calculate a "corrected burn depth" as follows: $(A + B) - C [(A+B)/E] = C.B.D.$

Measurements A, B, C, D, E and the corrected burn depth were added to the data base¹. The histopathological grading definitions along with mean experimentally observed burn depths are found in Table I. A second transformation was made to the burn depths as follows: $[Corrected BD/(A+B)] * 2000 = N.B.D.$ This

¹A more detailed discussion of the histopathology grading system can be found in USAARL Report 78-11, June, 78. Abstract App. B.

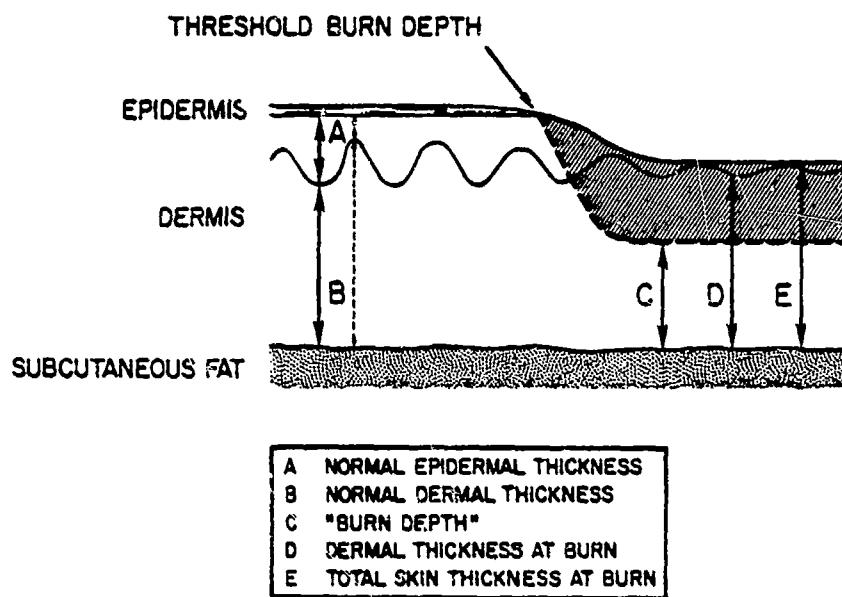


Figure 1. Schematic Diagram of Porcine Skin Showing Location of Measurements A through E recorded for each biopsy specimen.

TABLE 1
HISTOPATHOLOGICAL AND BURN DEPTH GRADING DEFINITIONS

Grade	Description	Approximate Depth (μm)		
		Nominal Range	Mid-Range	Mean Normalized Corrected
0	No thermal damage	0	0	-----
1	Cell damage without acidophilism	1-20	10	-----
2	Partial epidermis acidophilism	20-50	37.5	-----
3	Complete epidermal acidophilism	50-100	75	70 86
4	Partial dermal-epidermal separation	100-150	125	73 90
5	Complete dermal-epidermal separation	150-250	200	62 75
6	Superficial dermal	250-500	400	416 467
7	Mid-dermal	500-1000	800	894 1037
8	Deep dermal	1000-1500	1300	1400 1547
9	Complete dermal to adipose border	1500-2000	1800	2000 2160
10	Adipose	<2000	2000	2000 2375

"normalized burn depth" corrected for the large variability in total skin thickness (A+B). Normalized burn depth was added to the data base.

2.3 CORRECTIONS TO ORIGINAL DATA

2.3.1 Shutter Dynamics.

There were four different shutter propulsion systems employed during this study. In a study of the fire simulator/shutter system (see Abstract, Appendix B) correction factors were derived for each shutter system and each burn site location. These correction factors were applied to each exposure time in the data base so that the time represents the best estimate of actual exposure time ignoring complicating factors such as day to day variations in exposure time caused by changes in the rolling/sliding friction of the shutter.

2.3.2 Initial Skin Temperature.

Initial skin temperature has been shown to be an important factor in determining the energy requirements for a given level of burn damage (12). Skin temperatures were recorded at one of the burn sites for each exposure beginning 5 September 1972. No such recording was made prior to that date. A multiple linear regression analysis (see Table II) was used to derive a relationship between environmental factors (order of burn, time of day, temperature at Carins AAF, % humidity, wind velocity and % cloud cover) and measured skin temperature for pigs burned subsequent to 5 Sept 1972. This relationship was then used to calculate a predicted skin temperature for those pigs burned during July and August. This temperature was inserted into the data base.

2.3.3 Hair Removal.

Two different hair removal procedures were used during the course of the experiment and this resulted in mean hair length of 3.2mm for pigs burned in July and August and 1.75mm for the remaining pigs. In the first case, only about 93.75% of the incident radiation gets to the skin while in the latter case, 96.5% does so (4). Hair length for each pig is in the data base to aid in correcting the incident heat flux.

2.4 DATA MANAGEMENT COMPUTER PROGRAMS

In order to edit, retrieve, sort, list and otherwise manage the data in the data base, and to retrieve and format data from digitized tapes, e.g. records of sensor output digitized from FM magnetic tape recordings, some 12 programs were written, primarily in FORTRAN IV. Their complete description including source listings and sample output may be found in a report entitled "Thermal Analysis

TABLE II
REGRESSION ANALYSIS OF PIG SKIN TEMPERATURES

FILE NAME: SKTSMRT.DAT ALL PIGS FOR SEPTEMBER AND OCTOBER 1972

MEANS	Order	Time	Temp.Cairns	% Hum.	Wind Vel.	% Cloud	Obs.Skin Temp.
	2.50	1163.34	79.34	53.44	4.54	55.57	90.44

STD. DEVIATIONS

	1.12	159.43	16.21	8.33	2.94	30.72	4.82
--	------	--------	-------	------	------	-------	------

CORRELATION MATRIX

	1	2	3	4	5	6	
1	1.000	0.033	0.041	-0.111	-0.037	-0.064	0.123
2	0.033	1.000	0.291	-0.348	0.102	0.113	0.471
3	0.041	0.291	1.000	-0.364	-0.236	-0.319	0.813
4	-0.111	-0.348	-0.364	1.000	0.446	-0.009	-0.410
5	-0.037	0.102	-0.296	0.446	1.000	0.331	-0.021
6	-0.064	0.113	-0.319	-0.069	0.331	1.000	-0.160

MULTIPLE R 0.961

MULTIPLE R SQUARE 0.912

STD.ERROR ESTIMATE 2.141

F VALUE OF REGRESSION 63.630

DF 6, 116.

PREDICTOR	REG. COEF	ST. COEF	T VALUE
1	0.371	0.175	2.121
2	0.003	0.002	1.526
3	0.442	0.025	17.387
4	-0.066	0.033	-1.981
5	0.420	0.036	4.662
6	0.038	0.008	4.753

INTERCEPT 51.068

OBSERVED PREDICTED RESIDUAL

OBSERVED	PREDICTED	RESIDUAL
94.30	94.62	-1.32
94.60	92.30	-2.30
94.60	91.45	-3.15
94.60	96.11	-0.69
95.60	93.59	+2.01
97.30	94.56	-2.74
98.80	96.11	-2.69
99.60	99.53	-0.27
100.00	93.73	3.73
100.00	92.52	1.52
100.00	95.12	-4.12
101.00	91.62	1.62
102.00	94.99	-2.99
103.00	94.79	-3.79
103.00	95.03	-2.03
103.00	95.23	-2.23
103.00	98.35	-0.67
105.00	95.35	-0.65
104.00	91.26	3.26
104.00	91.00	3.00
103.00	92.61	-0.39
103.00	91.31	-0.79

Program: Computer Programs for Data Base Manipulation" (see Appendix B for an abstract). A one page sample listing of the primary data base is shown as Table III. The group (GRP) number in the last column is a quality control rating from 1 to 9. A rating of 4 indicates prime quality data which was collected during the summer months when the experimental protocol was undergoing considerable development. For a complete listing of the data base which includes a discussion of all the quality scores, see a report entitled "Experimental porcine burn injury data base: listings and graphic representation." (see abstract in Appendix B).

3.0 GRAPHIC PRESENTATION OF THE DATA BASE

A computer graphing program, PLOTS, allows the user to plot any two variables on arithmetic or log axes parameterized by a third variable if desired. The following examples give an indication of complexities and the basic variability inherent in the data. Vertical bars indicate sample means and the individual data points are indicated with a symbol instead of a bar for ± 1 standard deviation or ± 1 standard error of the mean. The first four plots show gross (clinical) and micro (histopathologic) grades versus normalized and corrected burn depth. In all cases there is a logical progression, though not linear, from low grades and shallow depth to high grades and deep burn depths.

Both systems apparently lack precision in distinguishing degrees of shallow, i.e. epidermal burn. It turns out that this is mostly a function of the burn depth measurement scheme in which C (see Figure 1) is measured from fat/dermal border up to epidermal border and stops there. Thus there is no really accurate, quantitative depth measurement when damage is limited to some fraction of the epidermis. For more discussion of this and other "Pitfalls in the use of the USAARL Histopathology Grading System", see abstract in Appendix B.

The next two plots relate burn grade to total heat flux. Again there is a logical progression with more severe burns requiring more energy to produce them. Neither of these representations reveals the difference between the burns resulting from one second at $8 \text{ cal/cm}^2 \cdot \text{sec}^{-1}$ versus 8 seconds at $1 \text{ cal/cm}^2/\text{sec}$. Since reciprocity has been shown not to hold (13), there is reason to believe that the picture is more complex. Moreover, none of these plots takes into account such uncontrolled variables as initial skin temperature, length of time anesthetized, length of hair, etc. All these other variables have, most probably, contributed to the noisiness of the data.

The next plot compares the gross and micro grading systems. The correlation between them is quite good ($r^2 = .99$) from gross grade 6 through 16 and micro grade 4.5 to 10. There are so few data points below this level that it is not possible to draw any conclusion regarding the relationship between gross and micro grades.

The next four plots are an attempt to explore the relationship among three variables, flux, exposure time, and burn grade or depth. The log exposure time

TABLE III

GROSS GRADE VS. NORMALIZED BURN DEPTH

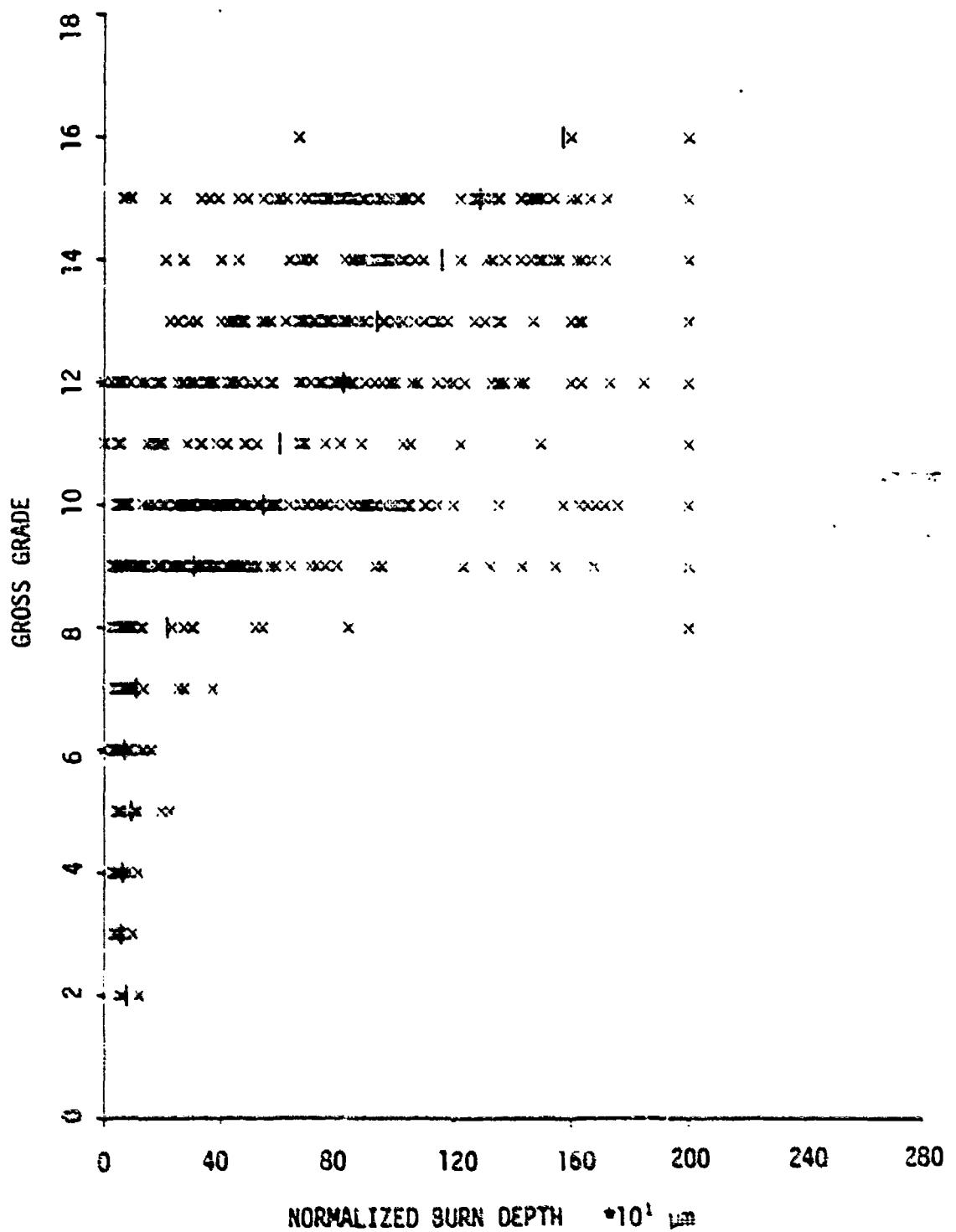


Figure 2.

GROSS GRADE VS. CORRECTED BURN DEPTH

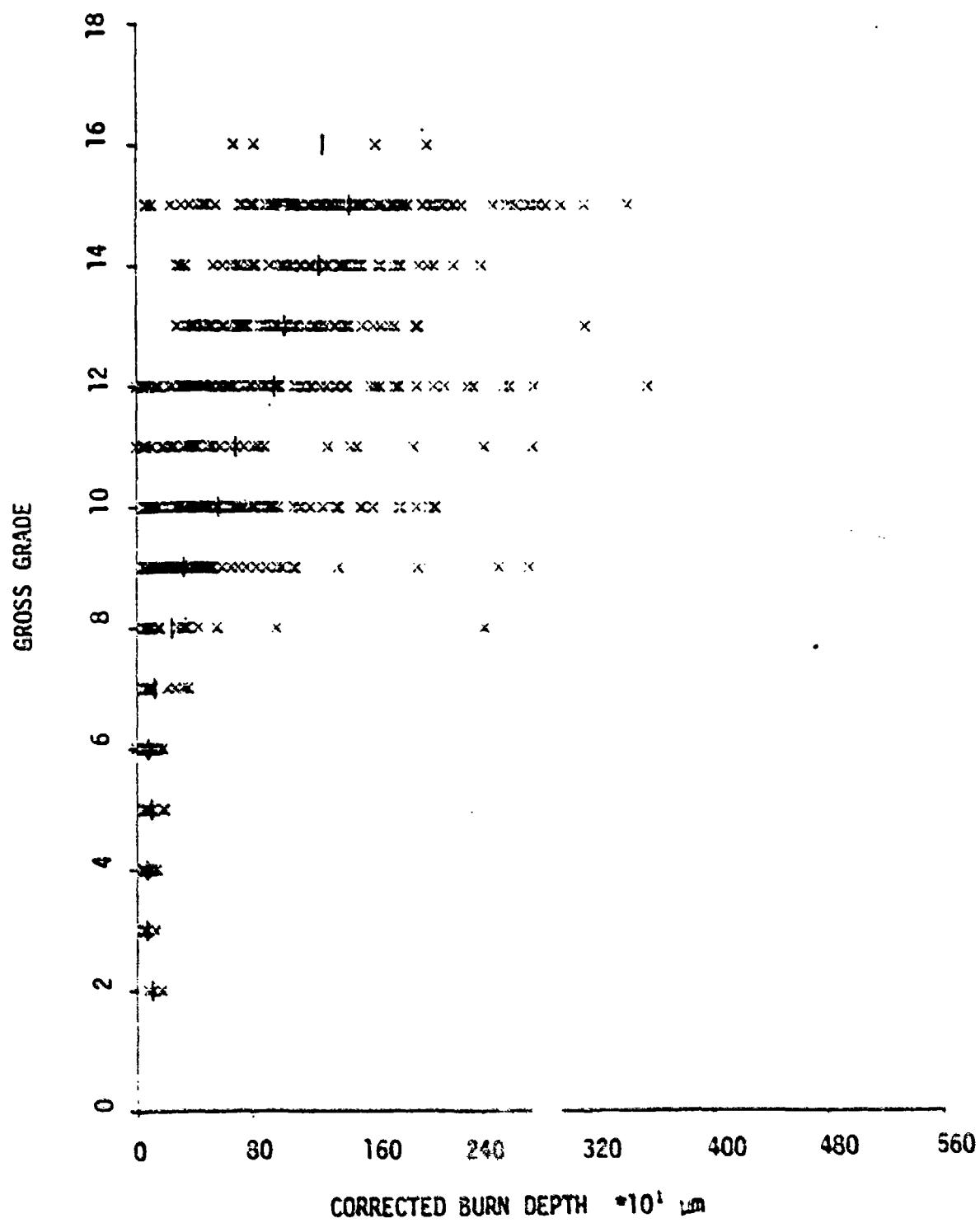


Figure 3.

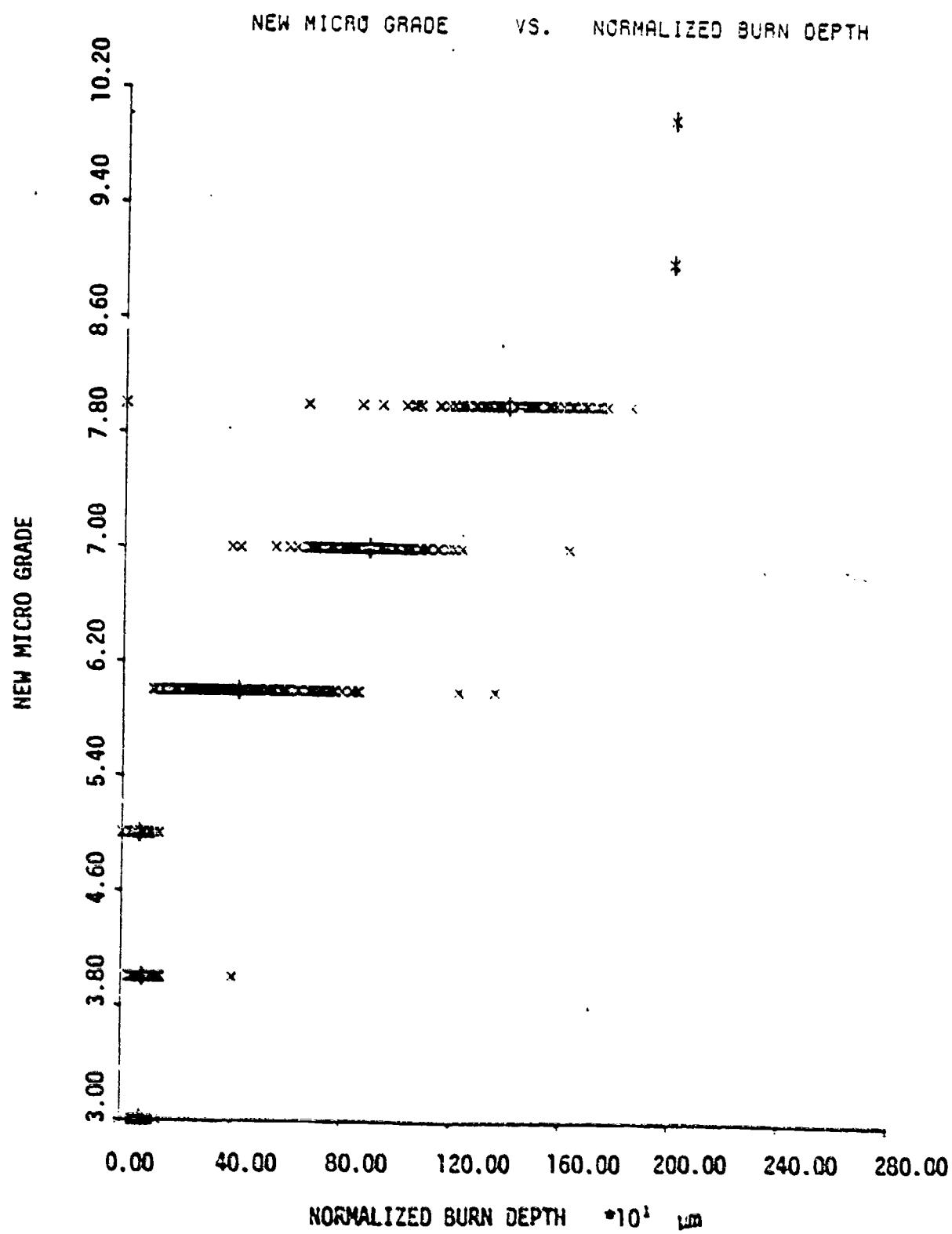


Figure 4.

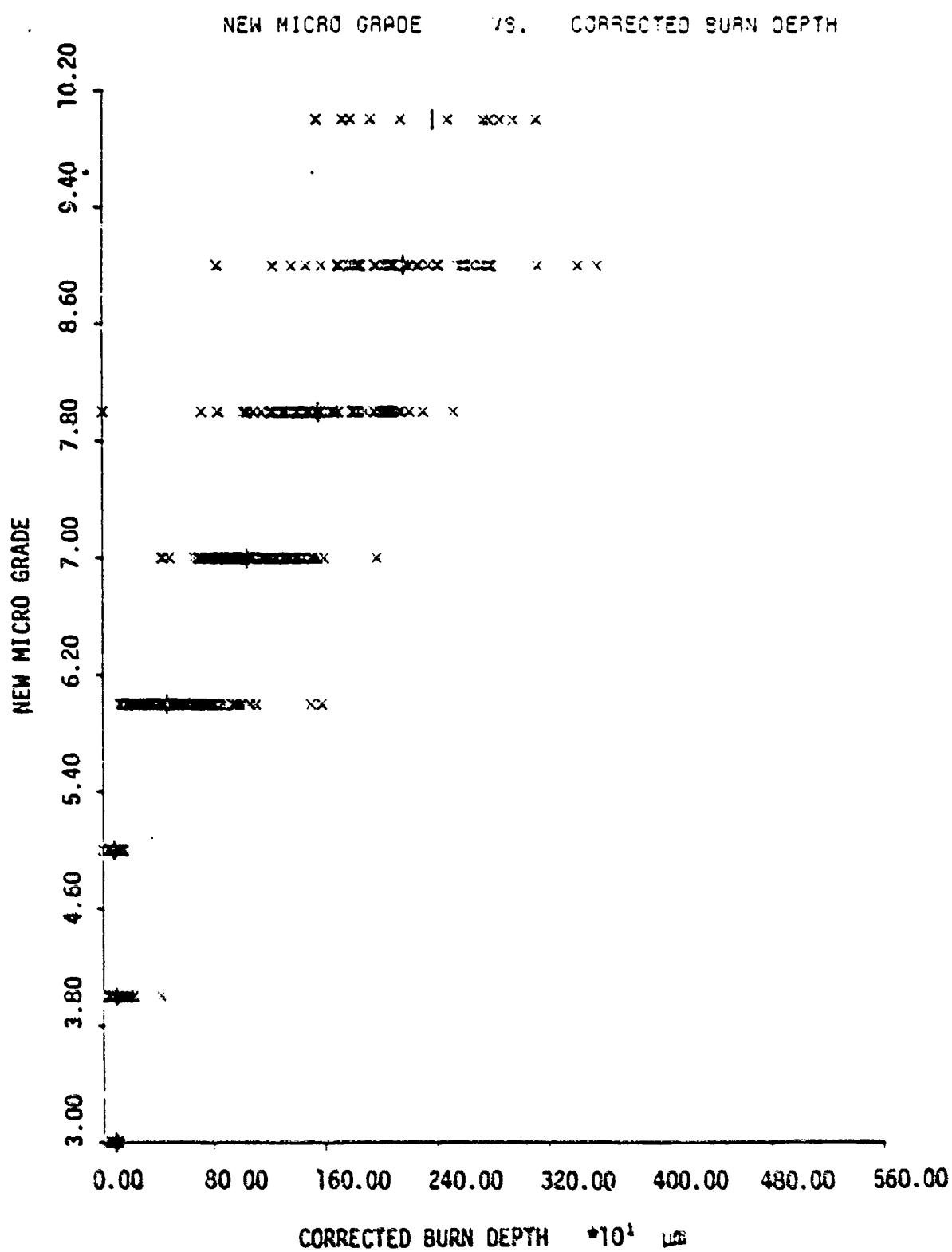


Figure 5.

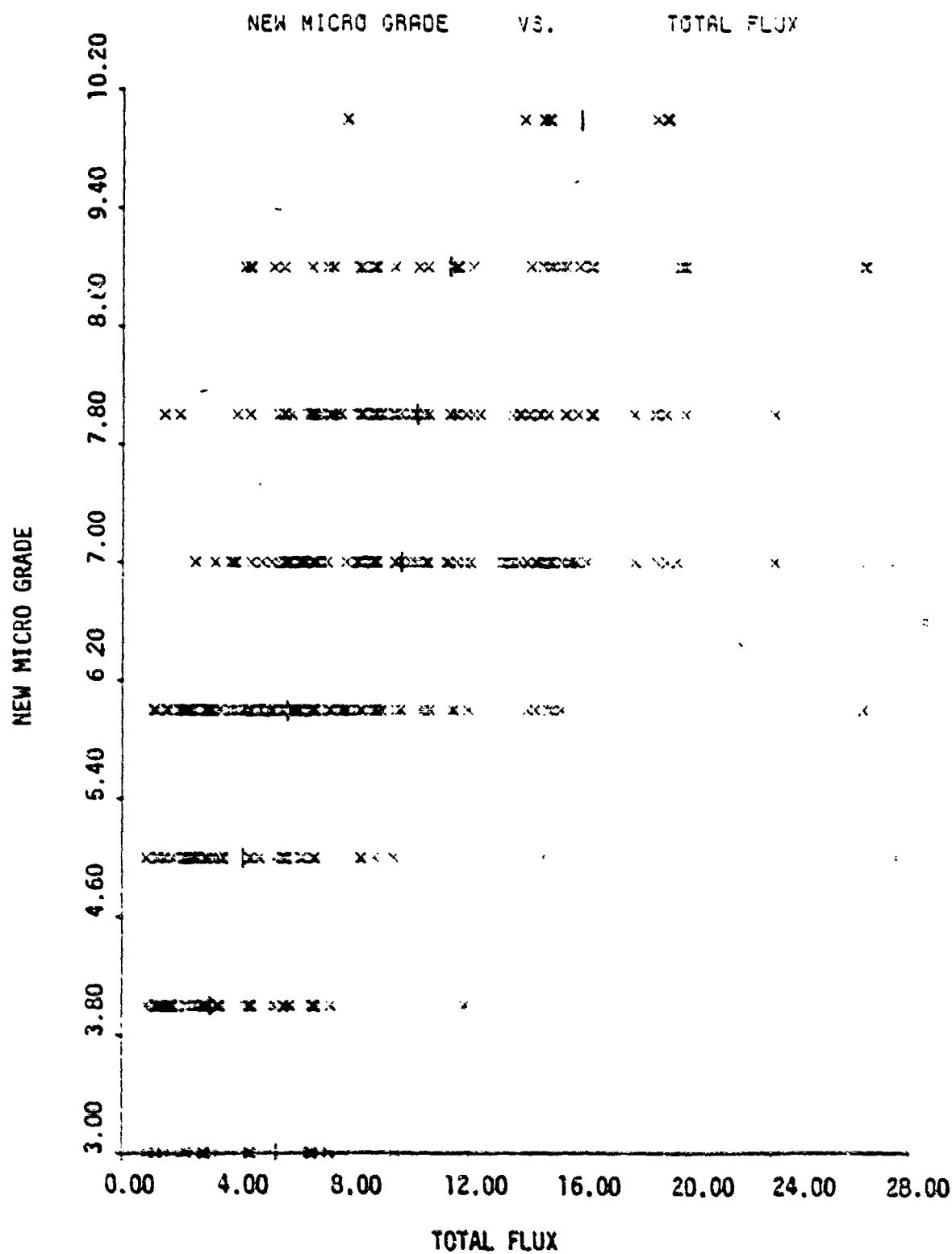


Figure 6.

GROSS GRADE VS. TOTAL FLUX

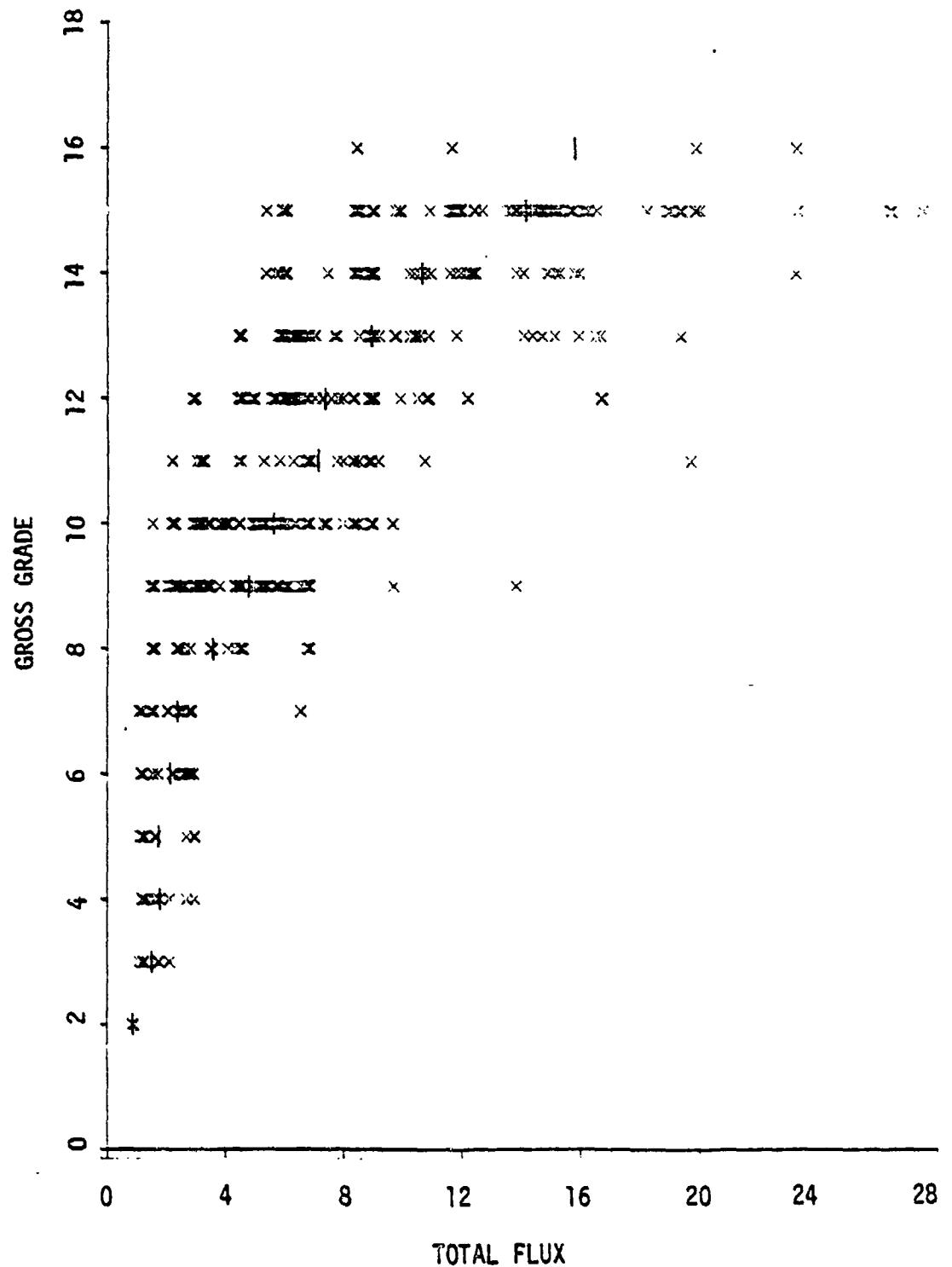


Figure 7.

GROSS GRADE VS. NEW MICRO GRADE

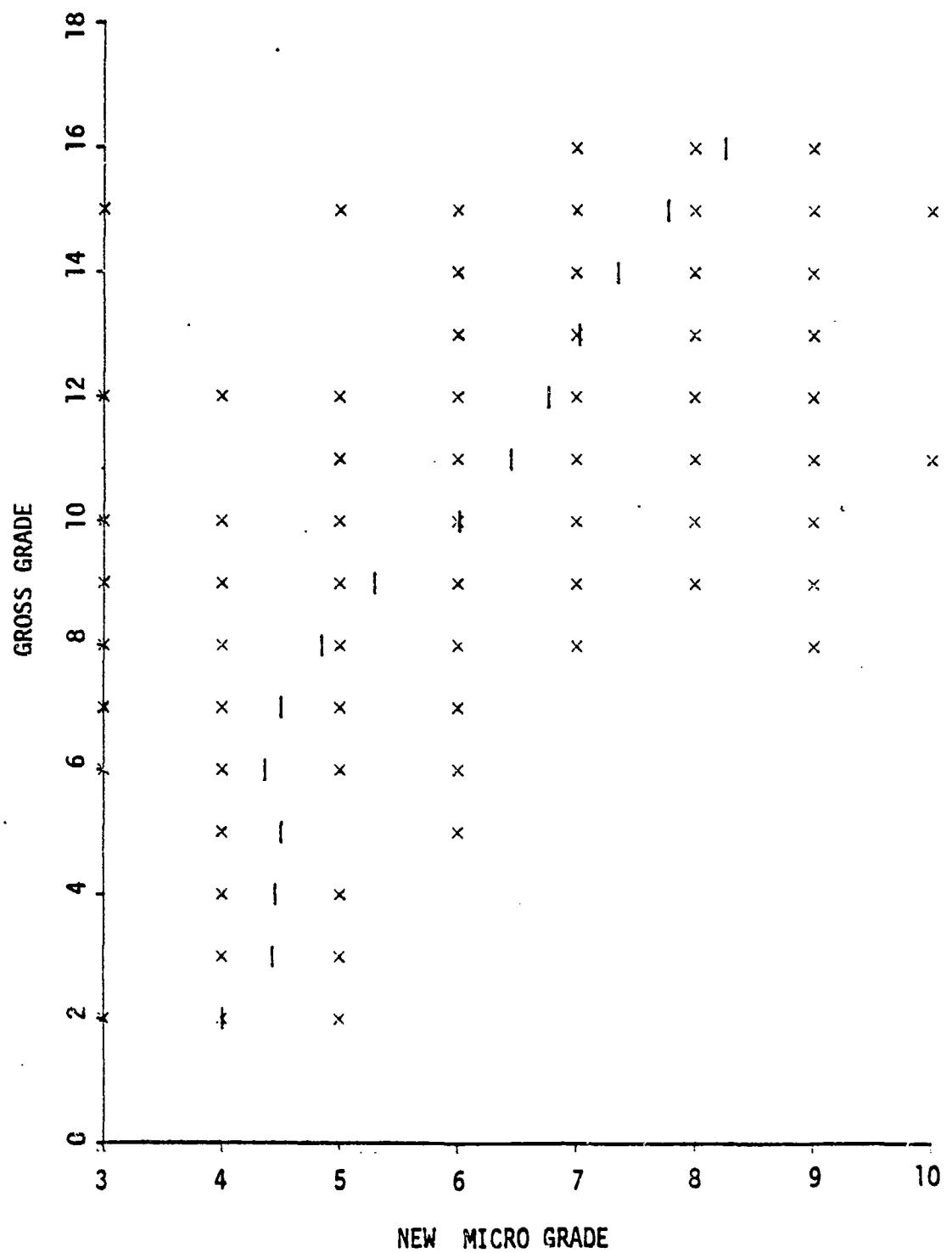


Figure 8.

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 4

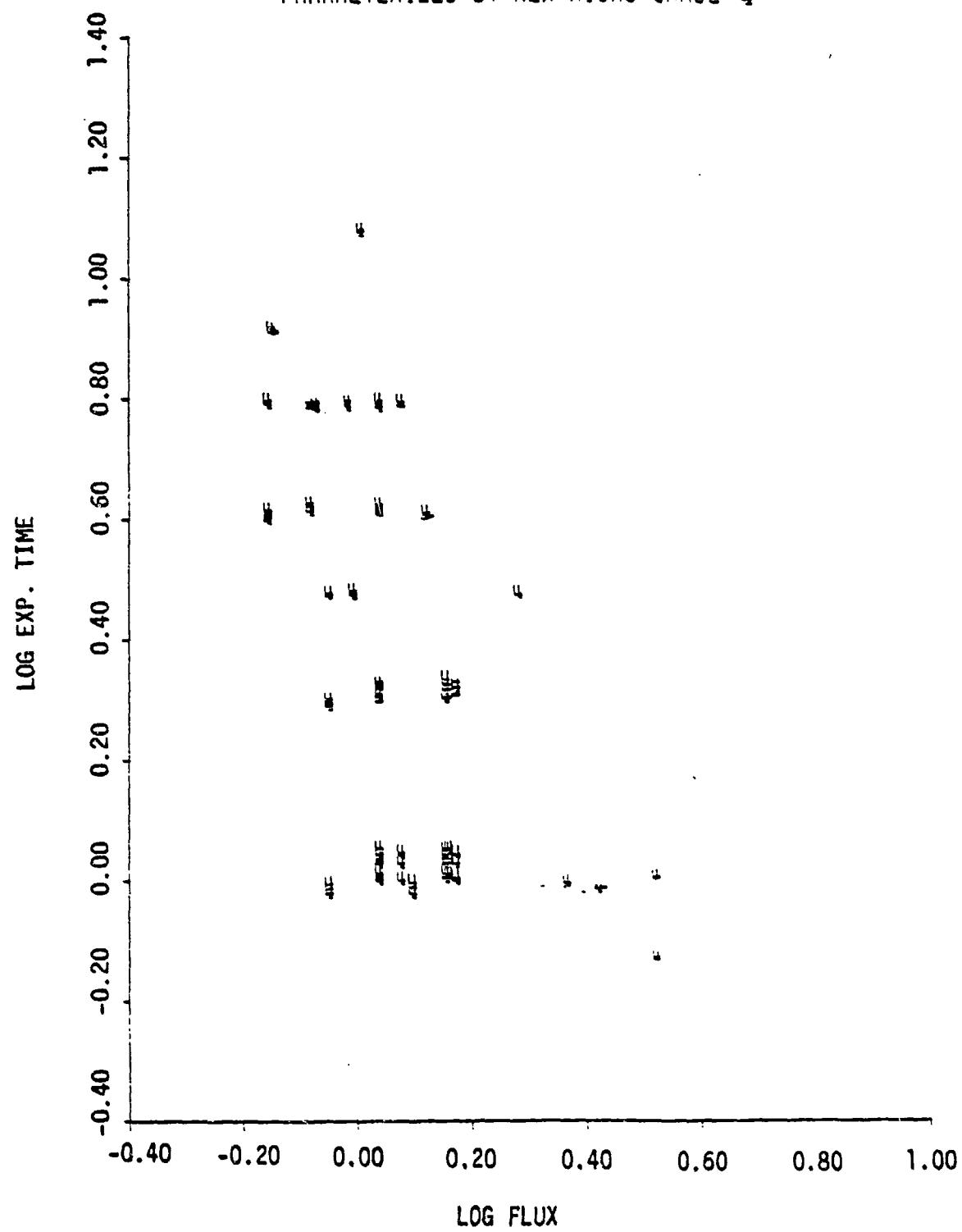


Figure 9.

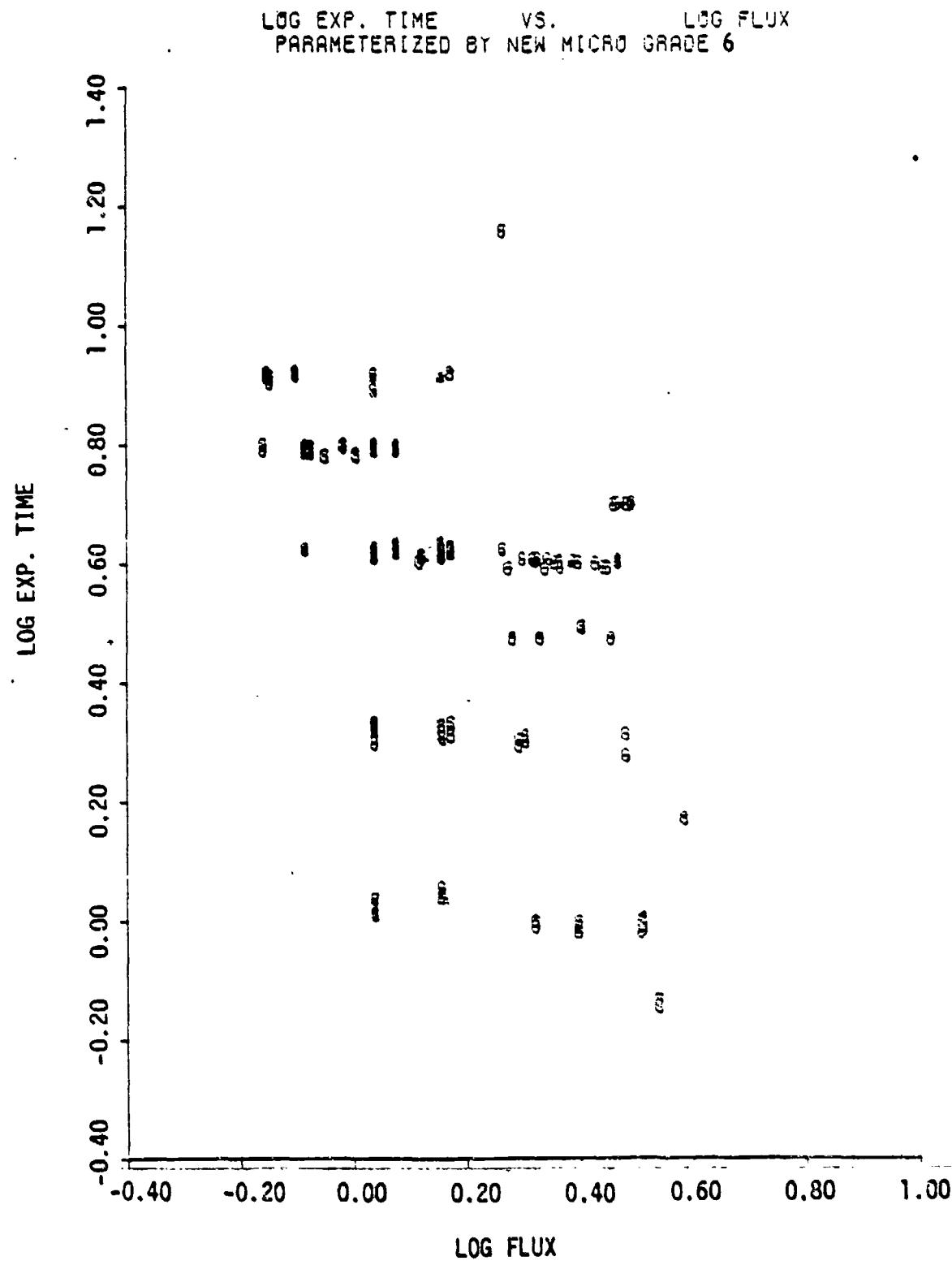


Figure 10.

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 9

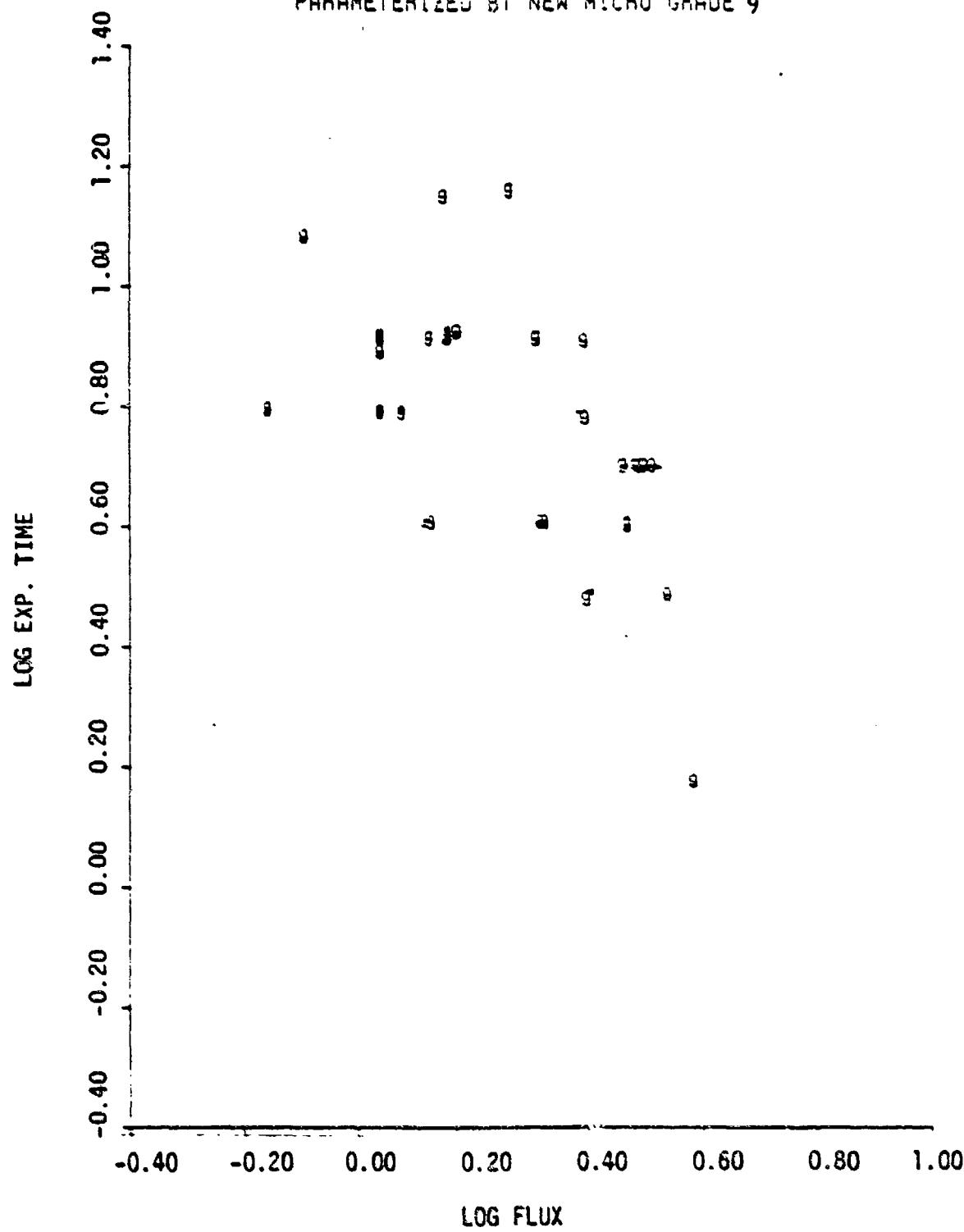


Figure 11.

NORMALIZED BURN DEPTH VS. TOTAL FLUX
PARAMETERIZED BY EXPOSURE TIME

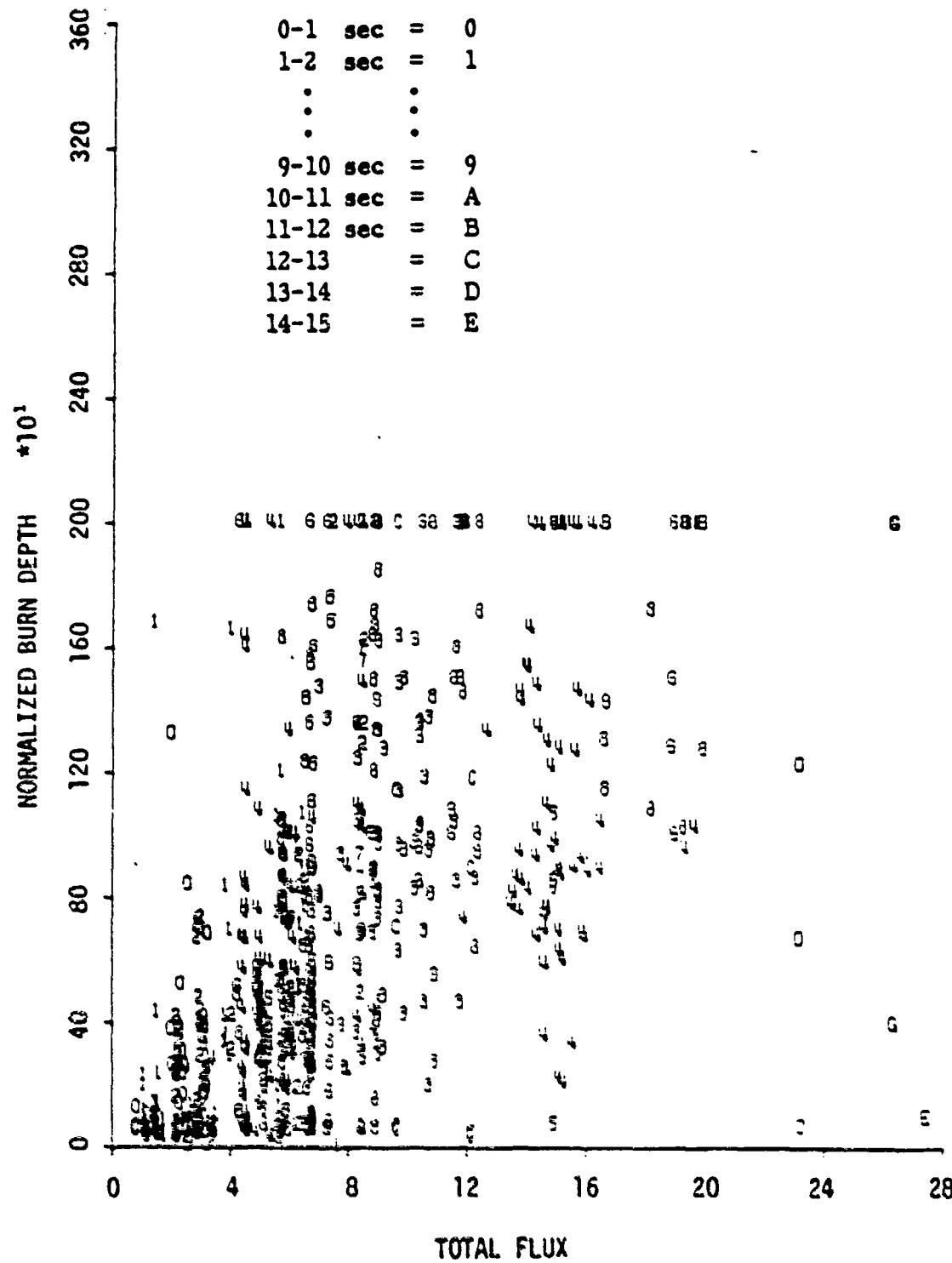


Figure 12.

vs. log flux parameterized by burn grade plots were suggested by Alice Stoll (14) based on her experience with pain thresholds and threshold blister burns. In her plots these two parameters form straight lines which are essentially parallel. The USAARL data suggests a shift to the upper right as a function of burn depth as might be expected but there also appears to be a slight change in slope of the "best" (drawn by eye) straight line from one burn level to the next.

The last plot (figure 12) is a different view of the same data, namely: normalized depth versus total flux parameterized by exposure time. While there is a progression to the data, it is largely obscured by the internal variability.

4.0 EMPIRICAL MODEL

The lack of really clear cut relationships in the foregoing graphical analysis, prompted the development of a multidiscriminant model which takes into account not only time, flux, total flux and burn grade, but includes furnace wall temperature, skin temperature and skin color as well. The results of applying this model to predict gross burn grade is shown in Table IV. The generalized Mahalanobis D-square, the equivalent of a Chi square for this sort of analysis, is highly significant showing that it is possible to predict with reasonable certainty the gross burn grade knowing exposure time, flux, furnace wall temperature, total flux, initial skin temperature, and skin color.

Multidiscriminant analysis was also applied to predict micro grades with a somewhat lower D-square but generally similar results. Both models were used to flag outlying data points for further checking against original records. However, neither model lends itself to use with an instrumented manikin and fire pit testing where the time-heat flux profiles recorded by the data acquisition system are not constant but change as the overlying fabrics react to the fire which is itself variable. In this case an analytical model is more suitable.

5.0 ANALYTICAL MODEL

Several years ago Weaver and Stoll (7) proposed an extension of Stoll's earlier model (6) to heat fluxes higher than used in obtaining the experimental data upon which the earlier model had been based. They also found that the effective conductivity changed during the exposure and subsequent cooldown period. Takata (15), using preliminary data from USAARL's Thermal Project (the uncorrected version of the current data base), formulated a model which not only predicted threshold burns but deep burns and tissue water boiling as well. Building on the work of Henriques (5), Stoll and Greene (6), Weaver and Stoll (7), Mehta and Wong (8) and Takata (15) we formulated an analytical model as follows:

For thermal exposures of interest, skin is essentially opaque to thermal radiation and can be considered to transfer energy internally by conduction only, since exposure durations are no longer than the minimum response times reported for increased thermoregulatory system activity (16). Consequently, thermal energy transfer in skin can be described by the heat conduction or Fourier equation. In rectangular coordinates, the Fourier equation may be written as follows:

$$p \cdot C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (K \frac{\partial T}{\partial x}) + q \quad (1)$$

where,

p = density, gm/cm³

C_p = heat capacity, cal/gm/°C

K = thermal conductivity, cal/cm-sec.°C

TABLE IV

DISCRIMINANT ANALYSIS...CROSS-BETWEEN GRADE									
NUMBER OF GROUPS = 3		Sample Sizes... Group		1		2		3	
NUMBER OF VARIABLES = 4		1		2		3		4	
GROUP	ITEMS	TYPE	FLUX	WALL T.	T.-%	SKIN T.	SKIN COLOR	COL	COL
1	0.877	0.612	1.120 .969	0.969	00.160	0.646	0.484	0.443	0.445
2	1.593	1.014	1.676 .977	2.469	00.621	0.613	0.521	0.515	0.515
3	2.049	3.002	1.829 .958	0.971	05.210	0.184	0.327	0.319	0.319
4	4.025	2.670	2.950 .977	0.981	01.265	0.168	0.168	0.168	0.168
5	6.866	5.169	1.623 .961	1.923	00.726	0.123	0.123	0.123	0.123
GENERALIZED MAPALAMONIS D-EGC...22									
DISCRIMINANT FUNCTION 1									
CONSTANT • COEFFICIENTS									
-315.981	*	0.467	-0.153	0.155	1.434	0.052	10.159	10.159	10.159
DISCRIMINANT FUNCTION 2									
CONSTANT • COEFFICIENTS									
-301.138	*	1.126	-0.157	0.154	0.016	0.026	10.261	10.261	10.261
DISCRIMINANT FUNCTION 3									
CONSTANT • COEFFICIENTS									
-301.138	*	1.126	-0.157	0.154	0.016	0.026	10.261	10.261	10.261
DISCRIMINANT FUNCTION 4									
CONSTANT • COEFFICIENTS									
-301.138	*	1.126	-0.157	0.154	0.016	0.026	10.261	10.261	10.261
DISCRIMINANT FUNCTION 5									
CONSTANT • COEFFICIENTS									
-301.138	*	1.126	-0.157	0.154	0.016	0.026	10.261	10.261	10.261

T = temperature, °C
 x = distance, cm
 q = energy source, for the first nodal volume, cal/cm³/sec

Since skin is considered to be opaque to radiant energy, and since the source term is due only to radiant energy¹, equation (1) applies only to the surface of the skin. For all conditions in which $x > 0$, equation (1) reduces to the following:

$$p \ C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (K \frac{\partial T}{\partial x}) \quad (2)$$

Solution of equations (1) and (2) requires two boundary conditions for x , preferably at $x = 0$ and $x = L$, and initial conditions at $t = 0$ for all positions $0 \leq x \leq L$. If one assumes that there is no backward flux of thermal energy at $x = 0$ (all conduction is into the skin), then the energy flux at $x = 0$ is zero and, consequently, $\partial T / \partial X = 0$. Similarly, if the problem assumes that an adiabatic backwell condition prevails at $X = L$, the fatty tissue, then the net flux out of the system at $X = L$ is 0, or $\partial T / \partial X = 0$. These two boundary conditions indicate that the system is closed and that all thermal energy added to the system, $0 \leq x \leq L$, is distributed within the system and cannot escape.

Initial conditions are established by specifying a uniform temperature for all locations, $0 \leq x \leq L$, at time, $t = 0$.

Consequently, the system may be defined by the following mathematical model:

$$p \ C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (K \frac{\partial T}{\partial x}) + q \quad @ x = 0 \quad (3)$$

$$p \ C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (K \frac{\partial T}{\partial x}) \quad @ 0 \leq x \leq L$$

$$T = T_0, \quad 0 \leq x \leq L, \quad t = 0 \quad \text{Initial conditions}$$

$$\frac{\partial T}{\partial x} = 0, \quad x = 0, \quad 0 \leq t \leq x \quad \text{Boundary conditions 1}$$

$$\frac{\partial T}{\partial x} = 0, \quad x = L, \quad 0 \leq t \leq x \quad \text{Boundary conditions 2}$$

¹A simplifying assumption based on the predominance of the radiate mode of heating. May be less valid with fabrics. In actuality a correction is made to q to account for convective heating, surface absorptivity, and attenuation of radiant heating by hair.

6.0 SOLUTION OF MATHEMATICAL MODEL

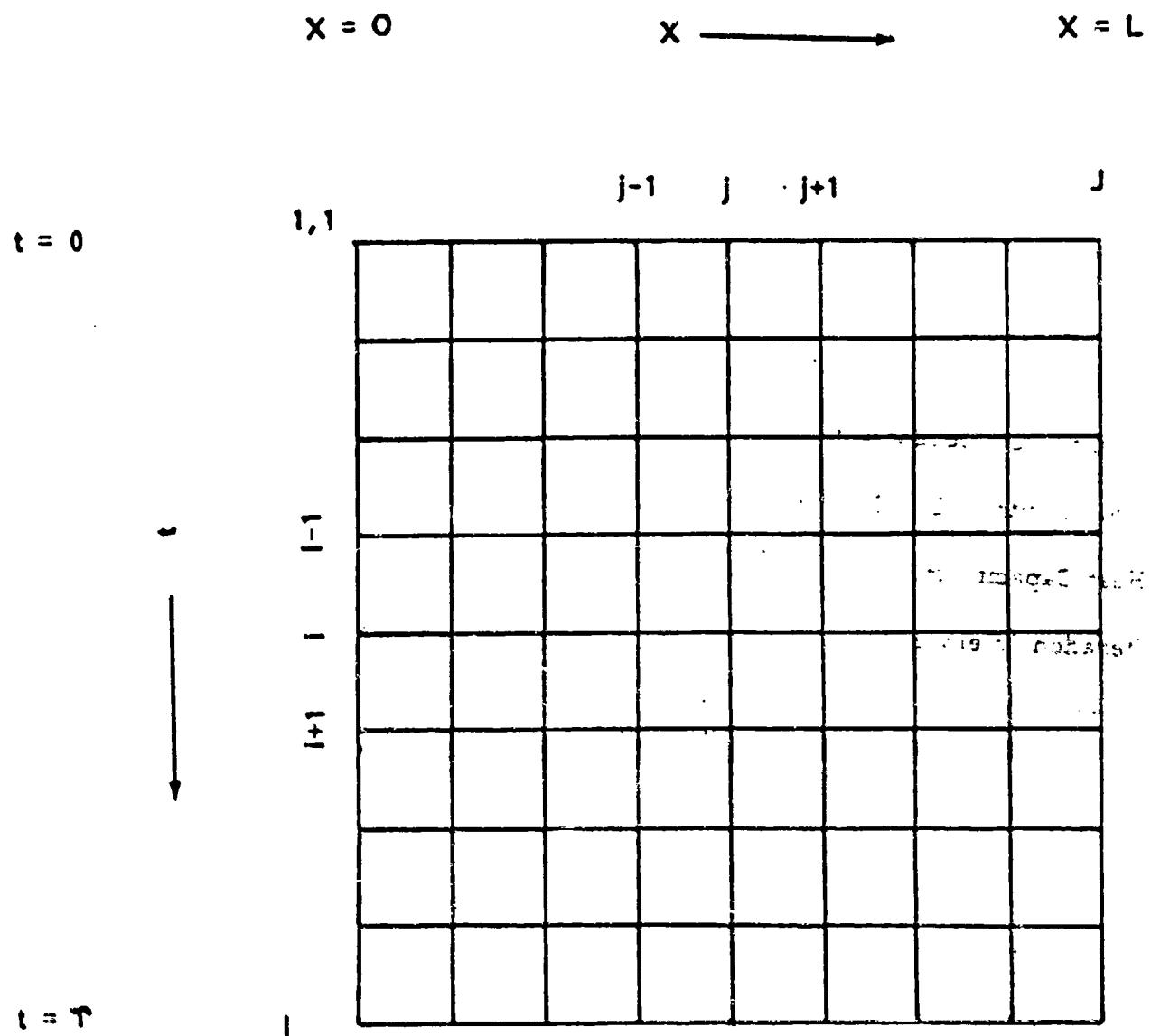
An analytical solution to equation set (3) was not considered feasible due to the variable nature of q , C_p and K ; so explicit differencing methods of numerical analysis were employed to solve the equations. Several investigators working with linear systems have found that the Crank-Nicholson six point implicit differencing method provided an excellent numerical solution (17). For the solution of equation set (3), the mathematical model, it was decided to apply the Crank-Nicholson method to the second order partial derivatives and corresponding explicit methods to the first order partials.

The grid work in Figure 13 is a representation of the differenced system from $X = 0$ to $X = L$ (J 's) and $t = 0$ to $t = y$ (i 's).

The Crank-Nicholson technique involves averaging the value of the dependent variable over the i and $i + 1$ row at a constant j position. The second order derivative is then evaluated at the $(j, i + 1/2)$ position. A forward difference formulation is applied to the $\partial T / \partial t$ term to match the same position.

The above described implicit differencing method is noted for the characteristics of stability and convergence. Correct increment sizes yield reliable convergence. The model was implemented in FORTRAN IV using solution techniques of Thomas as described by Bruce et al (18).

This initial model was revised to allow energy flux across the surface, $x = 0$, during heating, convective heat loss at the skin surface during cooling and heat transfer into deep tissues including conduction into fat, convective cooling via the blood, tissue water boiling, a temperature gradient from surface to fat and a gradient of thermal properties based on measured tissue water. For a complete description of the model including source listings, sample output and users manual, see a USAARL report entitled "BRNSIM - An Analytical Model for Predicting Thermal Cutaneous Injury", abstracted in Appendix B. The model, BRNSIM, is run interactively with the following variables changeable for each run:



GRIDWORK FOR NUMERICAL ANALYSIS

Figure 13.

TABLE V

MODEL PARAMETERS CHANGEABLE INTERACTIVELY

Initial Surface Temperature (TEMP10)

Density (ρ)Thermal Conductivity for each Node (BK_(i))

Node Depth (BL = 0.22 cm)

Heat Capacity for each Node (Cp_(i))

Iteration Interval (AK = 0.01 sec)

Number of Nodes (JINC = 12)

Exposure Time (ETIME)

Total Time (ITIME)

Water Boiling Temperature (°C)

Blood - Control Factor for Convective Tissue Cooling by Blood

TEMP B - Difference Between Backwall Tissue Temperature and TEMP10

Absorptivity of Surface

Incident Flux, Q, (cal/cm²/sec)Nxta Nodes - Number of Interpolated Nodes Between Surface and Node 2 -
Used for superficial burns.

Damage Rate Constants PL1, PLN1, PL2, PLN2, DE1, DE2

From the relationship for first order kinetics assumed to apply in damaging tissue protein we have: (5)

$$\text{damage rate} = \frac{d\Omega}{dt} = P e^{-\Delta E/RT}; \quad \text{total damage} = \int_0^{\text{ETIME}} \frac{d\Omega}{dt} dt + \int_{\text{ETIME}}^{\text{ITIME}} \frac{d\Omega}{dt} dt$$

if $P = N \times 10^y$ and $\Delta E/R = DE$

$$\text{then } \ln \frac{dw}{dt} = \ln N + y \ln 10 - \frac{\Delta E}{R} \cdot \frac{1}{T} = PL + PLN - DE \cdot \frac{1}{(T+273)}$$

Thus for damage calculations the following constants are entered: (15)

$$PL_1 (44^\circ\text{C} - 50^\circ\text{C}) = 1.46$$

$$PL_2 (50^\circ\text{C} - 100^\circ\text{C}) = 2.24$$

$$PLN_1 (44^\circ\text{C} - 50^\circ\text{C}) = 147.37$$

$$PLN_2 (50^\circ\text{C} - 100^\circ\text{C}) = 239.47$$

$$DE_1 (44^\circ\text{C} - 50^\circ\text{C}) = 50,000$$

$$DE_2 (50^\circ\text{C} - 100^\circ\text{C}) = 80,000$$

The program outputs $d\Omega/dt$, for each node at each time step, total is damage for each node and a threshold depth, where $\Omega = 1$. This depth, found using inverse interpolation on two or three Ω 's nearest 1 using either y or $\log(y)$.

Since its first presentations (19, 20) BRNSIM has undergone further development.

7.0 THERMAL PROPERTIES OF SKIN

Measurements of the water content of pig skin as a function of thickness were made on split thickness skin samples from several pigs.

Given a table of measured values of water content as a function of skin thickness, a least-squares cubic polynomial was fit to the data and water content as a function of depth was computed from the formula:

$$w(T-d) = \frac{T}{d} (W_T - W_{T-d}) + W_{T-d}$$

where T is the total thickness of a slab, W_T is the fraction of water computed from the cubic equation, d is the thickness of a thin slab at a depth $T-d$, and W_{T-d} is the fraction of water above the thin slab.

Thermal properties of the tissue were computed from the equations: (21)

$$1) \text{ density: } \gamma = \frac{w_w}{\gamma_w} + \frac{w_f}{\gamma_f} + \frac{w_p}{\gamma_p}^{-1}$$

$$2) \text{ heat capacity: } C_p = w_w C_{p_w} + w_f C_{p_f} + w_p C_{p_p}$$

$$3) \text{ thermal conductivity: } K = \gamma \frac{k_w w_w}{\gamma_w} + \frac{k_f w_f}{\gamma_f} + \frac{k_p w_p}{\gamma_p}$$

where the subscripts w, f, and p refer to water, fat, and protein, respectively. w_n is the mass fraction, γ_n the density, C_{p_n} the heat capacity, and k_n the thermal conductivity of the respective components. Values of the various terms used were:

$$\gamma_w = 1 \text{ gm/cc} \quad C_{p_w} = 1 \text{ cal/gm}^{\circ}\text{C}$$

$$k_w = 0.15 \times 10^{-3} \text{ cal/cm-sec}^{\circ}\text{C}$$

$$\gamma_f = 0.815 \text{ gm/cc} \quad C_{p_f} = 0.55 \text{ cal/gm}^{\circ}\text{C}$$

$$k_f = 4.5 \times 10^{-4} \text{ cal/cm-sec}^{\circ}\text{C}$$

$$\gamma_p = 1.54 \text{ gm/cc} \quad C_{p_p} = 0.26 \text{ cal/gm}^{\circ}\text{C}$$

$$k_p = 4.3 \times 10^{-4} \text{ cal/cm-sec}^{\circ}\text{C}$$

Fat and protein were assumed to be present in equal amounts so that:

$$W_f = W_p = \frac{1}{2}(1 - w_w),$$

and the resultant equations were:

$$\gamma = (6.18277 \times 10^{-2} w_w + .938172)^{-1}$$

$$K = \gamma(1.08432 \times 10^{-3} w_w + 4.15684 \times 10^{-4})$$

$$C_p = .595 w_w + .405$$

Using the equations above, the profile of thermal properties was calculated for skin depths of from 81 to 2290 μm . A linear extrapolation of tissue water content from a depth of 81 μm to the skin surface was made using a stratum corneum water content calculated from Rushmer et al (22) and the ambient % humidity during the experimental phase of the project. This calculated water profile was used to complete the calculation of thermal properties profile from 81 μm to the skin surface. These new thermal properties replaced those chosen by Morse et al (9) and used during previously reported simulations (19, 20). See the report entitled "Thermal Properties Calculated from Measured Water Content as a Function of Depth in Porcine Skin" as abstracted in Appendix B for additional details.

8.0 INTRASKIN TEMPERATURES

In earlier simulations (19, 20) it became apparent that unless the temperature calculations reasonably represented what actually occurred in the skin, adjustment of the values for PL, PLN and DE in the damage equation to match a few data

points would not be likely to result in a model which works well for all cases. Fortunately eleven intraskin temperature profiles were recorded on FM magnetic tape. These voltage records were digitized and converted to tables of temperatures at 100 samples per second. Figure 14 presents the one page summary report from a simulation of the exposure of Pig 294RF to a $3.47 \text{ cal cm}^{-2} \text{ sec}^{-1}$ fire for 3.02 seconds. Note that boiling occurred (confirmed by blister formation, Figure 15) and that the surface reached a maximum of 128.724°C . Predicted threshold depth was $1520\mu\text{m}$. Three observed temperature profiles are overlayed on the calculated temperature profiles (for nodal depths of 0, 220, 440... $2200\mu\text{m}$) in Figures 16, 17 18. The oscillations in the observed temperature profile are most probably due to a "hunting" in the autoregulation of tissue perfusion by blood. The frequency, for example, is similar to that seen in studies of microcirculation (23).

The next series of figures, 19-22, shows a simulation in which the intraskin temperature gradient, cooling by blood and water boiling are turned off. This time the temperature profile does not fit. The threshold depth is similar only because the heat flux is higher. (The comparable simulation with gradient, blood and boiling turned on had a Max. Temp. = 130.945 , Threshold depth = 1585 and a final time of 100). The next simulation (BRNSIM 3 vs M12VB0120, see Figures 23-26) is identical with the previous except that gradient, blood and boiling are turned on and the recalculation of skin thermal properties subsequent to water boiling is inhibited. Note that this simulation does not fit well either. Thus, only the complete model reasonably simulates the temperature profile.

Table VI presents a comparison on burns observed in the bioassay test with predictions of Model 3 (BRNSIM). This table is an updated version of one previously published (20) and includes normalized burn depth in addition to corrected burn depth. The effect of normalized burn depth in reducing the RMS Error can be seen in Table VII. One problem with Model 3 was noted in running case 296RF. The normal version of the model, labelled M12VB0120 or Model 3, includes a recalculation of thermal properties subsequent to boiling. This is done perceptibly following the cessation of boiling and in cases of high heat flux and moderate or longer exposure times; it acts as a pulse of heat flux causing an instability as can be seen in the temperature plot in Figures 27 and 28. A run with BRNSIM 3, which is Model 3 with the recalculation routine inhibited, results in a prompt, but perhaps too rapid, cooling of the skin following shutter closure (see Figures 29 and 30). This is not a problem in those cases when boiling does not occur. It can be fixed by redesigning the recalculation algorithm.

9.0 PREDICTIONS FROM SENSOR DATA

The next set of simulations used the digitized and converted output from Aerotherm Thermoman Sensors, a file of flux values as a function of time, to drive the model. Table VIII summarizes twenty simulations and compares the predicted depths with both normalized and corrected depths and Figure 31 shows the results of one simulation. Data produced by the older version, Model II, from Knox et al (20), is also included. As noted, columns IIIA and IIIB were run at slightly

MODEL NAME OR DESCRIPTION: MODEL 3 PIG 294RF DB VALUES ABS=.613 * INCIDENT FLUX 6 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP0= 34.9700
DENS= 1.00000
Q1= 3.47000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMPB= 3.3600
ABSORB= 0.613000
BOIL= 100.150

PL2= 2.24
PLN2= 239.42
PL1= 1.46
PLN1= 147.37
DE1= 80000.00
DE1= 50000.00
ETIME= 3.02
ITIME= 100.00
NXTRA= 8
BLOOD= 0.0000

EXTEN NODES: 22.2 44.4 66.7 88.9 111.1 133.3 155.6 177.8

FLUXFILE I.D.: 0.00000 0.00000

FLUXFILE I.D.: 0.00000 0.00000

FLUXFILE I.D.: 0.00000 0.00000

W= 0.39972E+01

W= 0.48734E+00

W= 0.49386E-01

D= 0.72442E+01

D= 0.73778E+01

D= 0.74955E+01

W =	0.19755E+19	AT DEPTH (IN MICRONS)=	0.112535E-06
W =	0.82484E+12	AT DEPTH (IN MICRONS)=	200.000
W =	0.26534E+09	AT DEPTH (IN MICRONS)=	400.000
W =	0.57126E+06	AT DEPTH (IN MICRONS)=	600.000
W =	0.84809E+04	AT DEPTH (IN MICRONS)=	800.000
W =	0.44495E+03	AT DEPTH (IN MICRONS)=	1000.00
W =	0.39339E+02	AT DEPTH (IN MICRONS)=	1200.00
W =	0.39372E+01	AT DEPTH (IN MICRONS)=	1400.00
W =	0.46754E+00	AT DEPTH (IN MICRONS)=	1600.00
W =	0.19306E-01	AT DEPTH (IN MICRONS)=	1800.00
W =	0.89937E-02	AT DEPTH (IN MICRONS)=	2000.00
W =	0.000000E+00	AT DEPTH (IN MICRONS)=	2200.00

MAXIMUM TEMPERATURE = 128.724

THRESHOLD DEPTH = 1520.

FINAL TIME = 100.00

Figure 14.



Figure 15. Intraskin thermocouple (0.003", "located superficially") shown prior to burn (left) and subsequent to exposure to $3.47 \text{ cal} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$ for 3.02 seconds (right).

Gross grade = 13 New Micro grade = 8 Threshold depth = $1465\mu\text{m}$

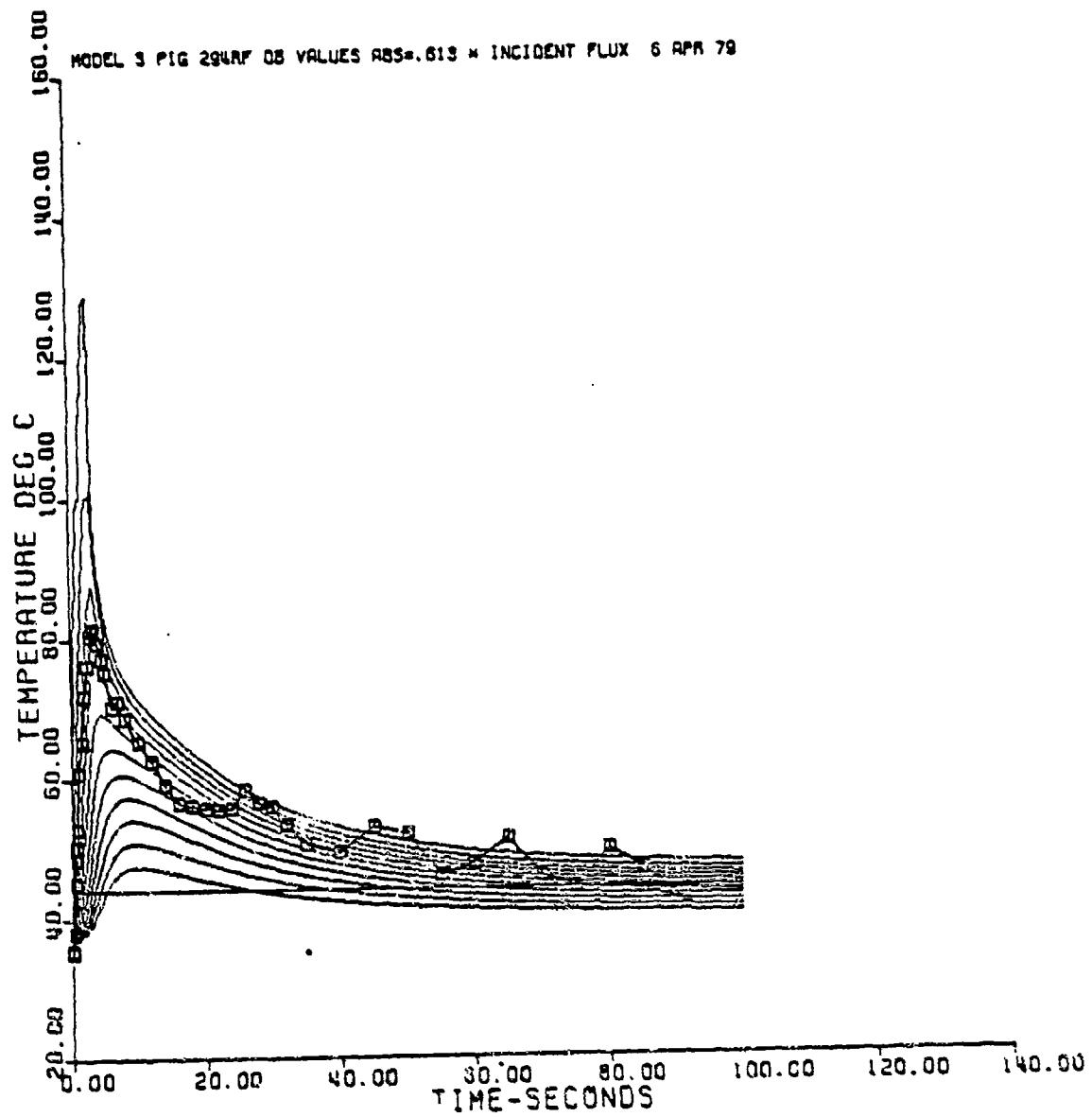


Figure 16.

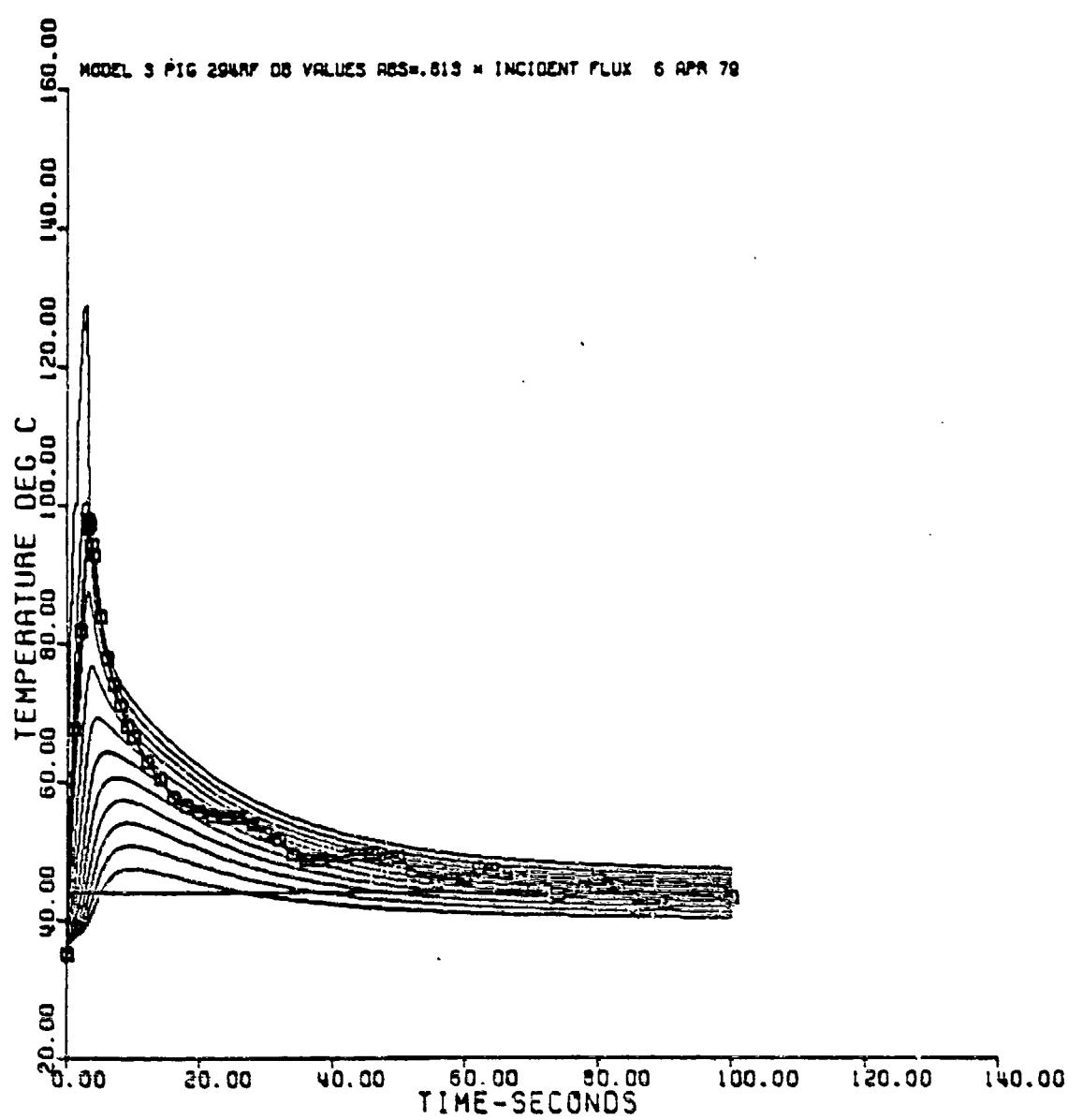


Figure 17.

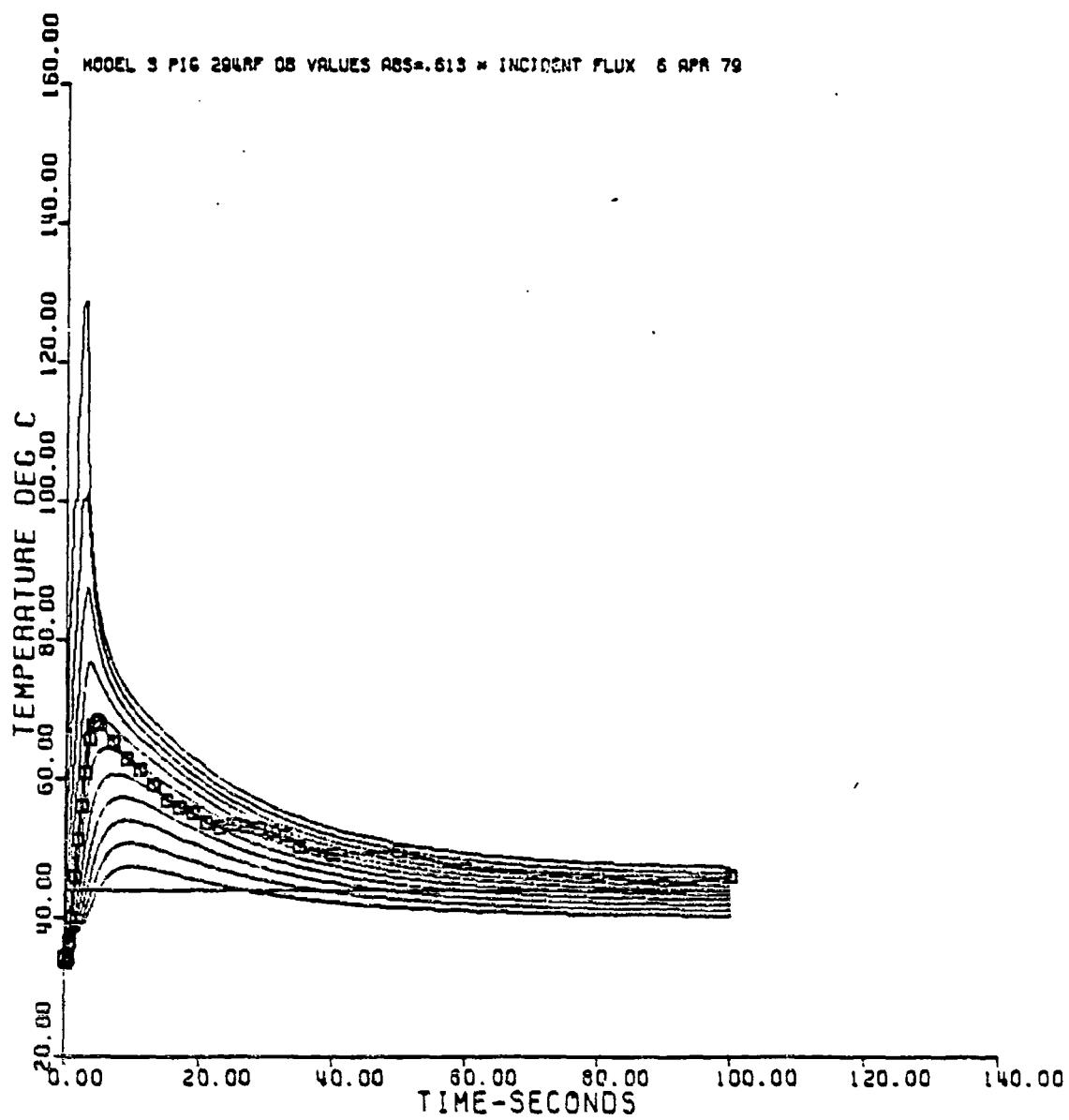


Figure 18.

MODEL NAME OR DESCRIPTION: M12VB9129 FIG 294 *27.28.29 WITH TEMPB,BLOOD=0 AND BOIL=250 4 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 34.9700
DENS= 1.00000
Q1= 3.74000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMPB= 0.0000
ABSORB= 0.613000
BOIL= 250.000

PL2= 2.24
PLH2= 233.47
PL1= 1.46
PLIII= 147.37
DE2= 00000.00
DE1= 50000.00
ETIME= 3.02
ITIME= 100.00
NXTRA= 0
BLOOD= 0.0000

FLUX FILE I.D.: 8.00 2

FLUX(I)=
1 3.740 2 3.740

W= 0.89104E+01
W= 0.46214E+00
W= 0.26098E-01

D= 0.72442E+01
D= 0.73770E+01
D= 0.74955E+01

W =	0.36075E+22	AT DEPTH (IN MICRONS)=	0.112535E-06
W =	0.20134E+17	AT DEPTH (IN MICRONS)=	200.000
W =	0.41975E+12	AT DEPTH (IN MICRONS)=	400.000
W =	0.11413E+09	AT DEPTH (IN MICRONS)=	600.000
W =	0.32822E+06	AT DEPTH (IN MICRONS)=	900.000
W =	0.50035E+04	AT DEPTH (IN MICRONS)=	1000.00
W =	0.18057E+03	AT DEPTH (IN MICRONS)=	1200.00
W =	0.89104E+01	AT DEPTH (IN MICRONS)=	1400.00
W =	0.46214E+00	AT DEPTH (IN MICRONS)=	1600.00
W =	0.26098E-01	AT DEPTH (IN MICRONS)=	1800.00
W =	0.31424E-02	AT DEPTH (IN MICRONS)=	2000.00
W =	0.80800E+00	AT DEPTH (IN MICRONS)=	2200.00

MAXIMUM TEMPERATURE = 158.249

THRESHOLD DEPTH = 1547.

FINAL TIME = 38.12

Figure 19.

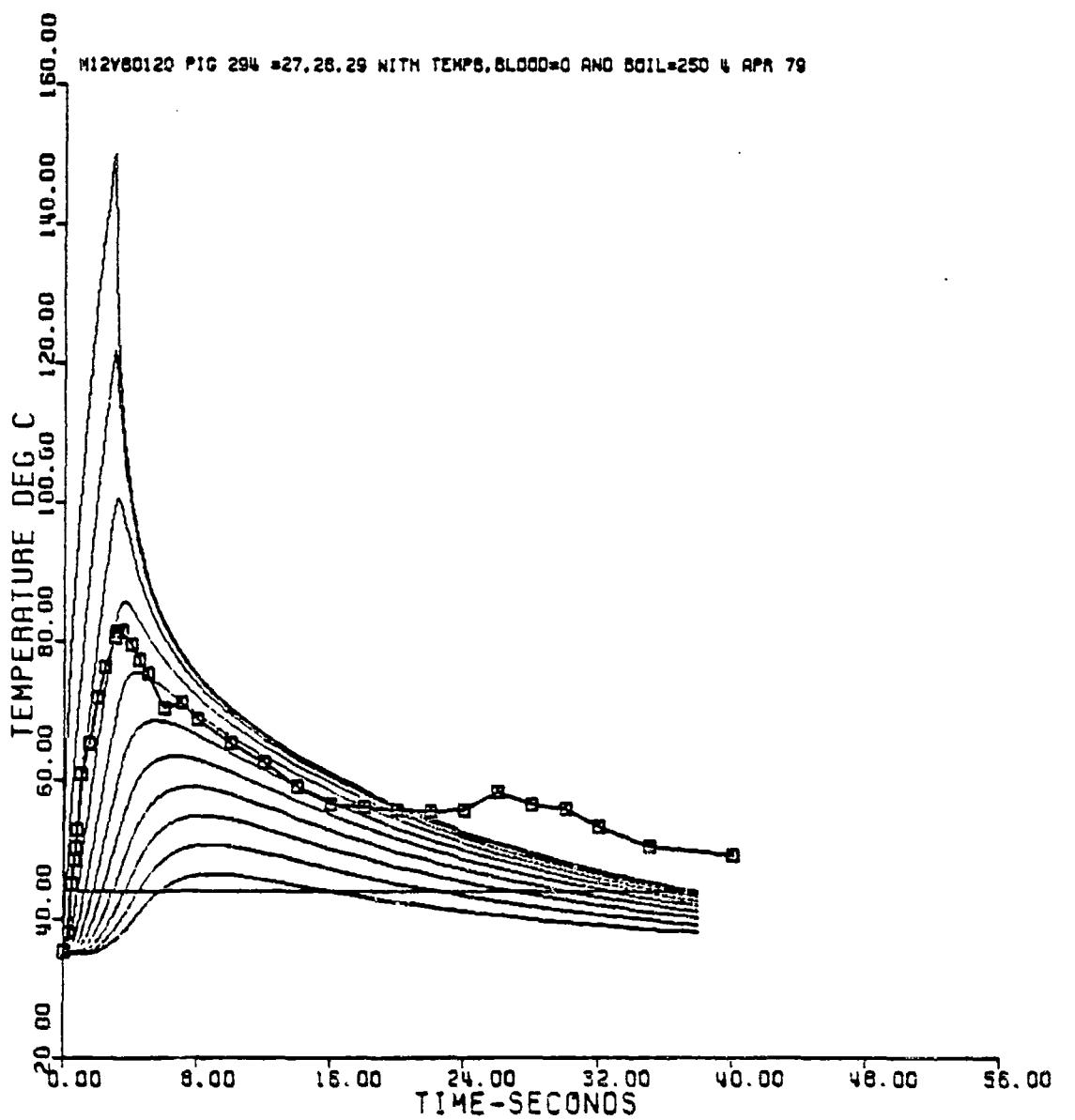


Figure 20.

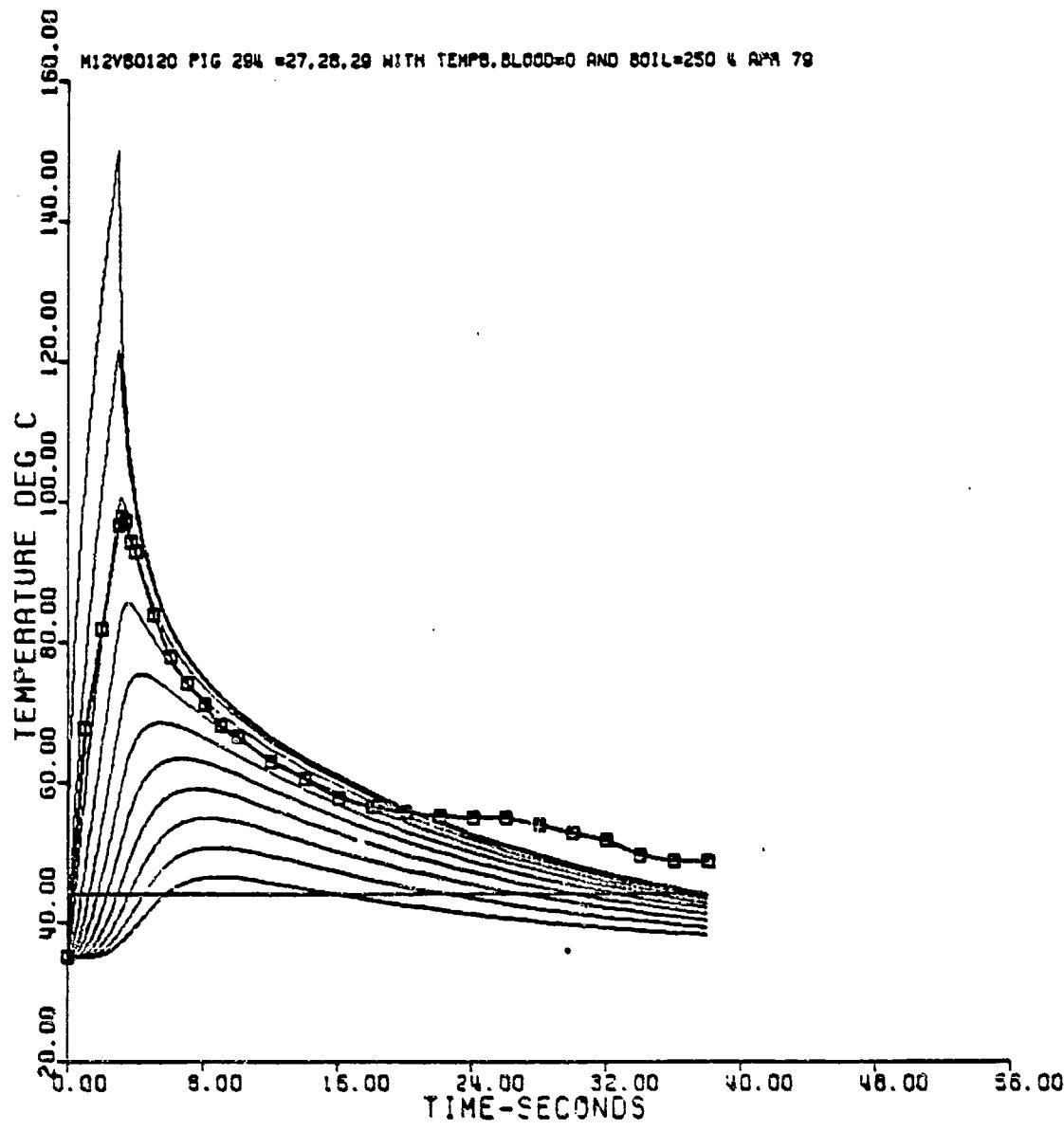


Figure 21.

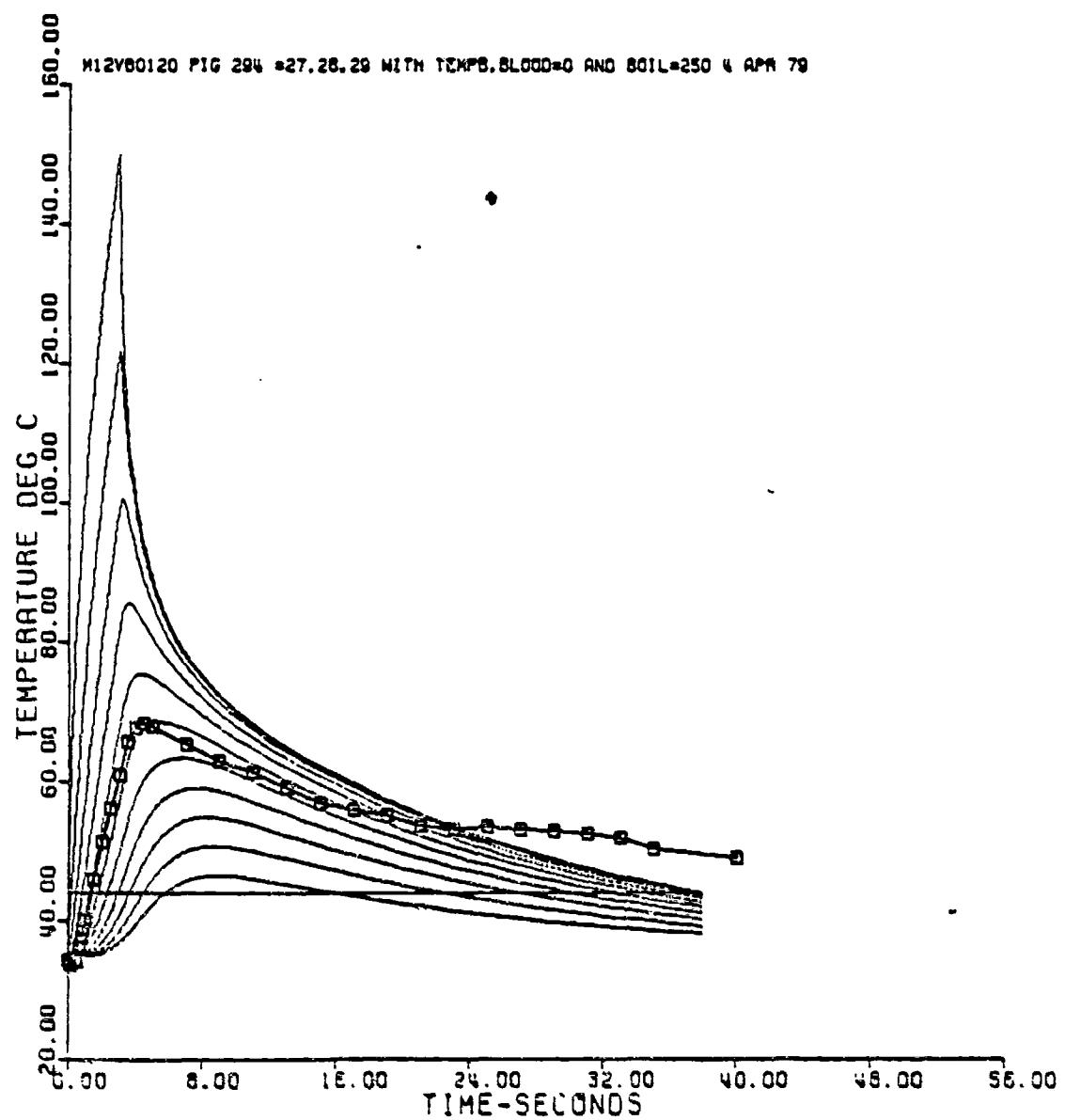


Figure 22.

MODEL NAME OR DESCRIPTION: BRNSIM3 PIG 294 #27.28.29 DB CORRECTED VALUES ABS=.613 VS M12/88128 5 APR

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP0= 34.9700
DENS= 1.00000
Q1= 3.74000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMPB= 3.3600
ABSORB= 0.613000
BOIL= 100.150

PL2= 2.24
PLN2= 239.47
PL1= 1.46
PLN1= 147.37
DE2= 80000.00
DE1= 50000.00
ETIME= 3.02
ITIME= 100.00
NXTRA= 0
BLOOD= 0.0010

FLUX FILE I.D.: 0.00 2

FLUX(1)=
1 3.740 2 3.740

H= 0.18514E+01
H= 0.19398E+00
H= 0.23789E-01

D= 0.72442E+01
D= 0.73778E+01
D= 0.74955E+01

H = 0.74177E+19 AT DEPTH (IN MICRONS)= 0.112535E-06
H = 0.10368E+13 AT DEPTH (IN MICRONS)= 200.000
H = 0.36773E+03 AT DEPTH (IN MICRONS)= 400.000
H = 0.69683E+06 AT DEPTH (IN MICRONS)= 600.000
H = 0.70257E+04 AT DEPTH (IN MICRONS)= 800.000
H = 0.23842E+03 AT DEPTH (IN MICRONS)= 1000.00
H = 0.19083E+02 AT DEPTH (IN MICRONS)= 1200.00
H = 0.18514E+01 AT DEPTH (IN MICRONS)= 1400.00
H = 0.19398E+00 AT DEPTH (IN MICRONS)= 1600.00
H = 0.23789E-01 AT DEPTH (IN MICRONS)= 1800.00
H = 0.32324E-02 AT DEPTH (IN MICRONS)= 2000.00
H = 0.00000E+00 AT DEPTH (IN MICRONS)= 2200.00

MAXIMUM TEMPERATURE = 138.837

THRESHOLD DEPTH = 1453.

FINAL TIME = 33.93

Figure 23.

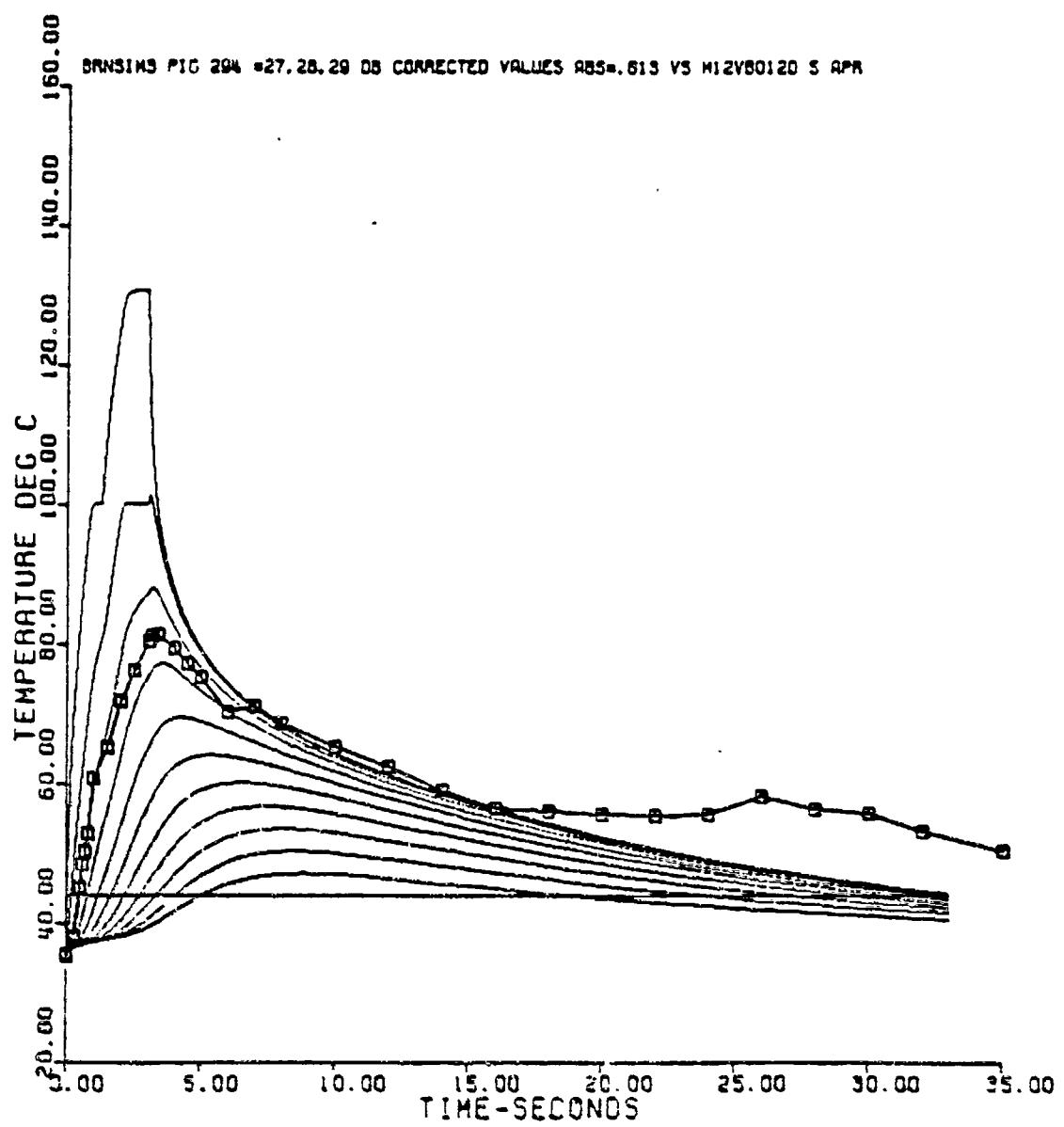


Figure 24.

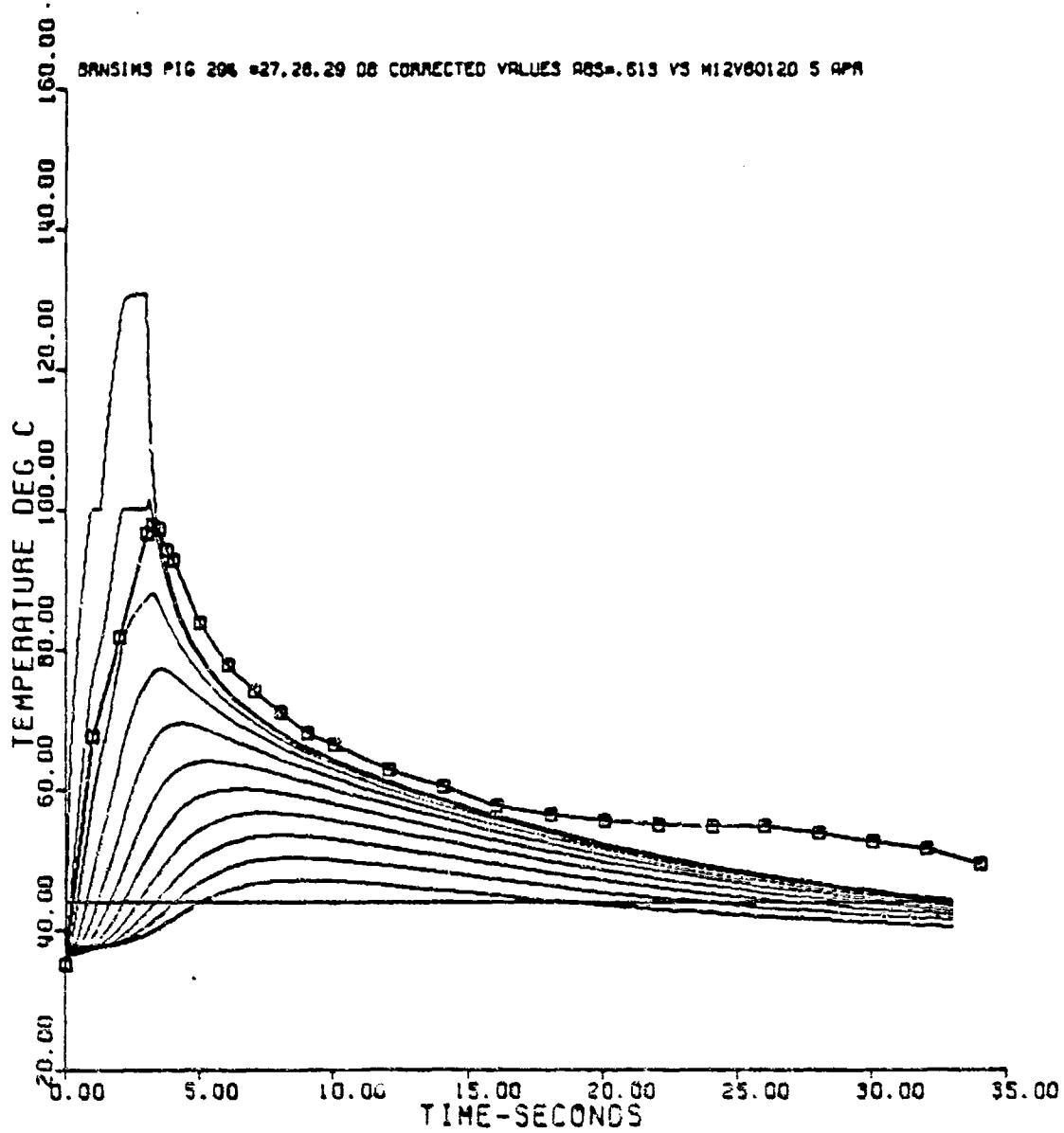


Figure 25.

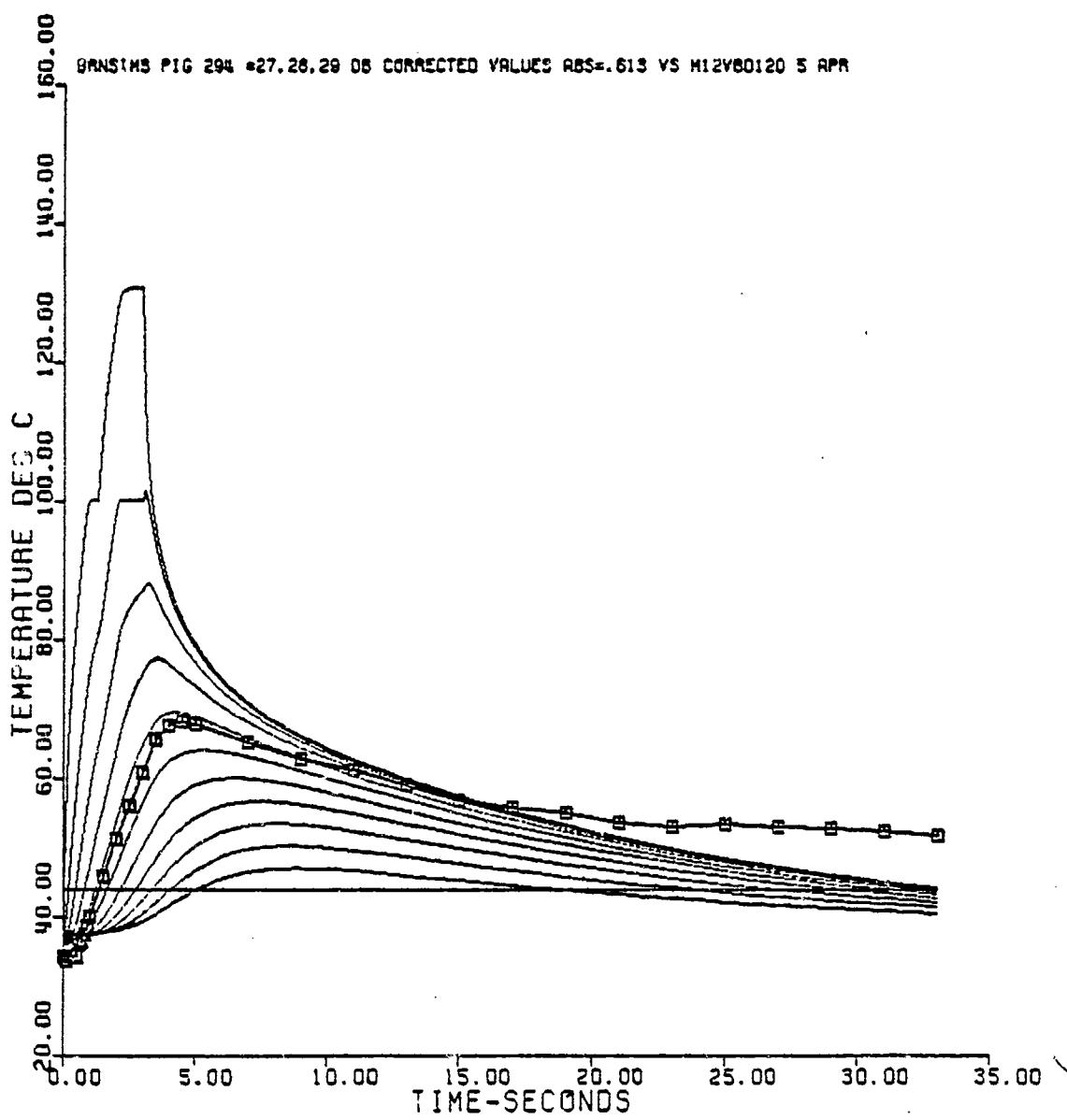


Figure 26.

TABLE VI. Comparison of burns observed in bioassay test with predictions of Model 3.

Pig	Exposure Time (s) ⁺	Incident Flux (cal cm ⁻² s ⁻¹)	Observed Burn Depth			N	Skin Surface Temp. (°C)	Core Temp. (°C)	Predicted Surface Absorptivity (10 ⁻⁴ cm)(°C)max.	Recorded Total Temp. (°C) [*] Time (s) Max.
			Normalized (10 ⁻⁴ cm) ⁺	Corrected (10 ⁻⁴ cm) ⁺	Normalized (10 ⁻⁴ cm) ⁺					
296LF	3.07±.02	2.55	523±362	611±414	3	28.1	38.0	.613	960	105.57
296LR	0.99±.02	2.64	71±7*	72±7	5	26.1	38.0	.613	151	75.57
296RF	8.2±.02	2.36	1804±437	2411±748	5	27.8	38.0	.613	1775***	119.52
296RR	1.51±.02	2.34	72±30**	73±32	5	26.9	38.0	.613	247	80.76
294LF	0.98±.02	3.27	222±77	257±90	5	30.0(34.3)†	38.33	.613	364	93.13
294LR	0.73±.02	3.49	334±298	396±342	5	31.7(37.9)	38.33	.613	318	96.60
294RF	3.02±.02	3.47	1680±452	2827±795	2	29.4(34.97)	38.33	.613	1520	128.72
294RR	1.47±.02	3.86	1040±661	910±769	5	30.6(33.9)	38.33	.613	720	111.80

† Intraskin temperature at time 0.

+ Mean ± 1 s.d.

‡ Approximate depth of recording = 100–200 μm.

* From micro grade depth = 150–250 μm.
** From old micro grade depth = 250–400 μm; new micro grade depth = 150–250 μm.

*** For this simulation the routine to recompute thermal properties subsequent to water boiling was turned off (see text for discussion).

TABLE VII. EFFECT OF NORMALIZED DEPTH IN REDUCING RMS ERROR

RMS ERROR	Model 3	
Normalized Depth	217	208*
Corrected Depth	539	535*

*Using 200 μm instead of 71 μm for 296 LR and 300 μm instead of 72 μm for 296 RR.

MODEL NAME OR DESCRIPTION: MODEL 3 FIG 296RF DB VALUES ABS=.613 *INCIDENT FLUX 6 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 27.0000
DENS= 1.00000
Q1= 2.36000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMPB= 10.2000
ABSORB= 0.613000
BOIL= 100.150

PL2= 2.24
PLH2= 239.47
PL1= 1.46
PLH1= 147.37
DE2= 00000.00
DE1= 50000.00
ETIME= 8.20
ITIME= 80.00
NXTRA= 8
BLOOD= 0.0010

EXTRA NODES: 22.2 44.4 66.7 88.9 111.1 133.3 155.6 177.8

FLUX FILE I.D.: 0.81 2

FLUX(1)=
1 2.360 2 2.360

H= 0.35406E+02
N= 0.16466E+01
H= 0.28409E-01

D= 0.74955E+01
D= 0.75009E+01
D= 0.76962E+01

H=	0.11325E+18	AT DEPTH (IN MICRONS)=	0.112535E-06
N=	0.11508E+14	AT DEPTH (IN MICRONS)=	200.000
H=	0.43975E+12	AT DEPTH (IN MICRONS)=	400.000
H=	0.23339E+11	AT DEPTH (IN MICRONS)=	600.000
H=	0.18791E+10	AT DEPTH (IN MICRONS)=	800.000
H=	0.10182E+09	AT DEPTH (IN MICRONS)=	1000.00
H=	0.45823E+07	AT DEPTH (IN MICRONS)=	1200.00
N=	0.16297E+06	AT DEPTH (IN MICRONS)=	1400.00
N=	0.44789E+04	AT DEPTH (IN MICRONS)=	1600.00
H=	0.95405E+02	AT DEPTH (IN MICRONS)=	1800.00
H=	0.16466E+01	AT DEPTH (IN MICRONS)=	2000.00
H=	0.28409E-01	AT DEPTH (IN MICRONS)=	2200.00

MAXIMUM TEMPERATURE = 119.613

THRESHOLD DEPTH = 2825.

FINAL TIME = 80.00

Figure 27.

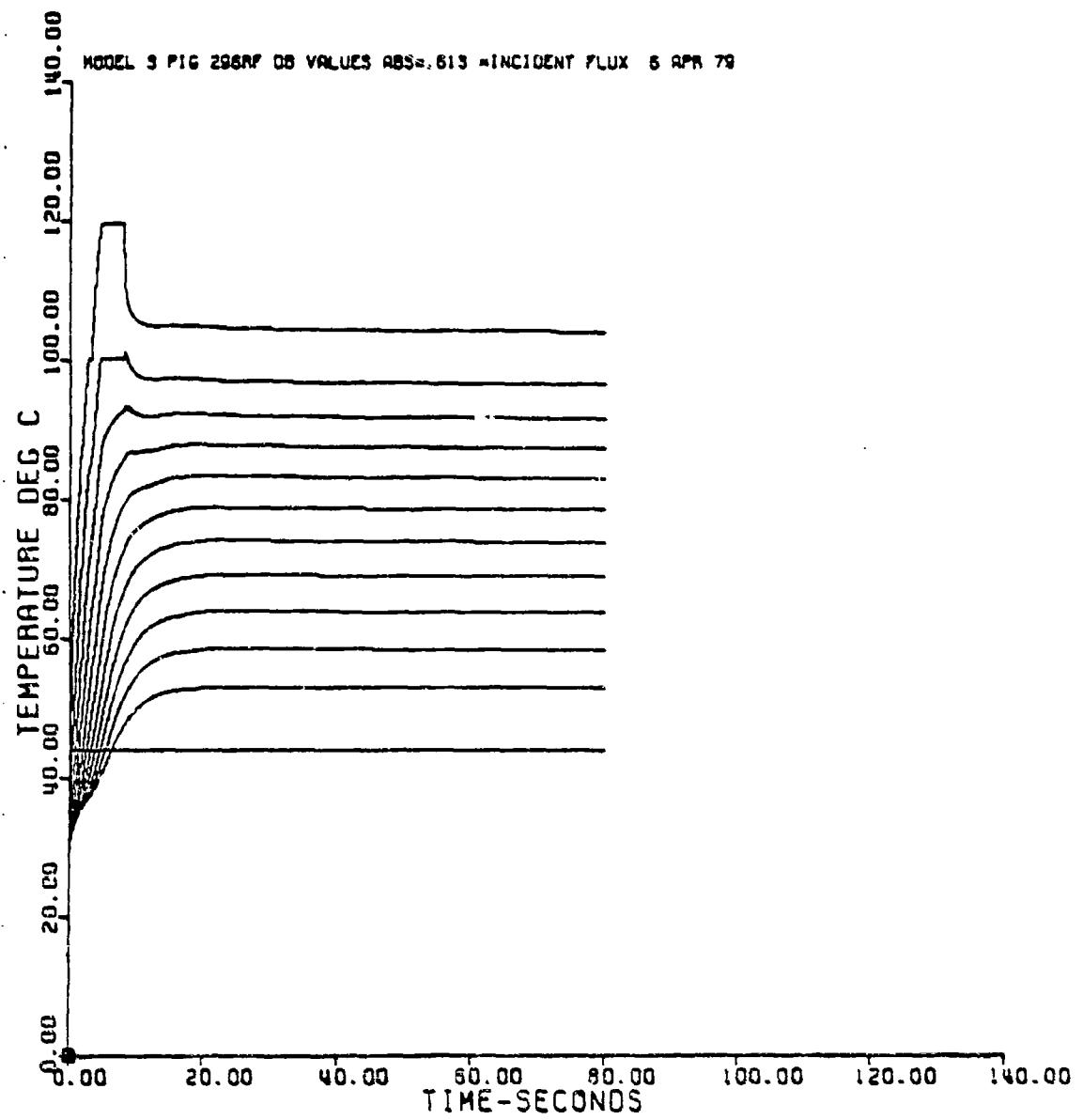


Figure 28.

MODEL NAME OR DESCRIPTION: BENSIM3 PIG 296BF DB VALUES ABS=.613 * INCIDENT FLUX 6 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 27.0000
DENS= 1.00000
Q1= 2.36000
SL= 0.220000
AX= 0.100000E-01
JINC= 12
TEMPB= 18.2000
ABSOFB= 0.613000
BOIL= 100.150

PL2= 2.24
PLH2= 239.47
PL1= 1.46
PLM1= 147.37
DE2= 80000.00
DE1= 50000.00
ETIME= 9.20
ITIME= 88.00
NXTPA= 0
BLOOD= 0.0010

FLUX FILE I.D.: 0.00 2

FLUX(1)=
1 2.368 2 2.368

W= 0.17115E+02
W= 0.66940E+09
W= 0.28309E-01

D= 0.73778E+01
D= 0.74955E+01
D= 0.76089E+01

W =	0.10648E+18	AT DEPTH (IN MICRONS) =	0.112535E-06
W =	0.31153E+13	AT DEPTH (IN MICRONS) =	200.000
W =	0.21686E+11	AT DEPTH (IN MICRONS) =	400.000
W =	0.31133E+09	AT DEPTH (IN MICRONS) =	600.000
W =	0.63479E+07	AT DEPTH (IN MICRONS) =	800.000
W =	0.22440E+06	AT DEPTH (IN MICRONS) =	1000.00
W =	0.30919E+04	AT DEPTH (IN MICRONS) =	1200.00
W =	0.40101E+03	AT DEPTH (IN MICRONS) =	1400.00
W =	0.17115E+02	AT DEPTH (IN MICRONS) =	1600.00
W =	0.66940E+09	AT DEPTH (IN MICRONS) =	1800.00
W =	0.28309E-01	AT DEPTH (IN MICRONS) =	2000.00
W =	0.13716E-02	AT DEPTH (IN MICRONS) =	2200.00

MAXIMUM TEMPERATURE = 119.315

THRESHOLD DEPTH = 1775.

FINAL TIME = 38.10

Figure 29.

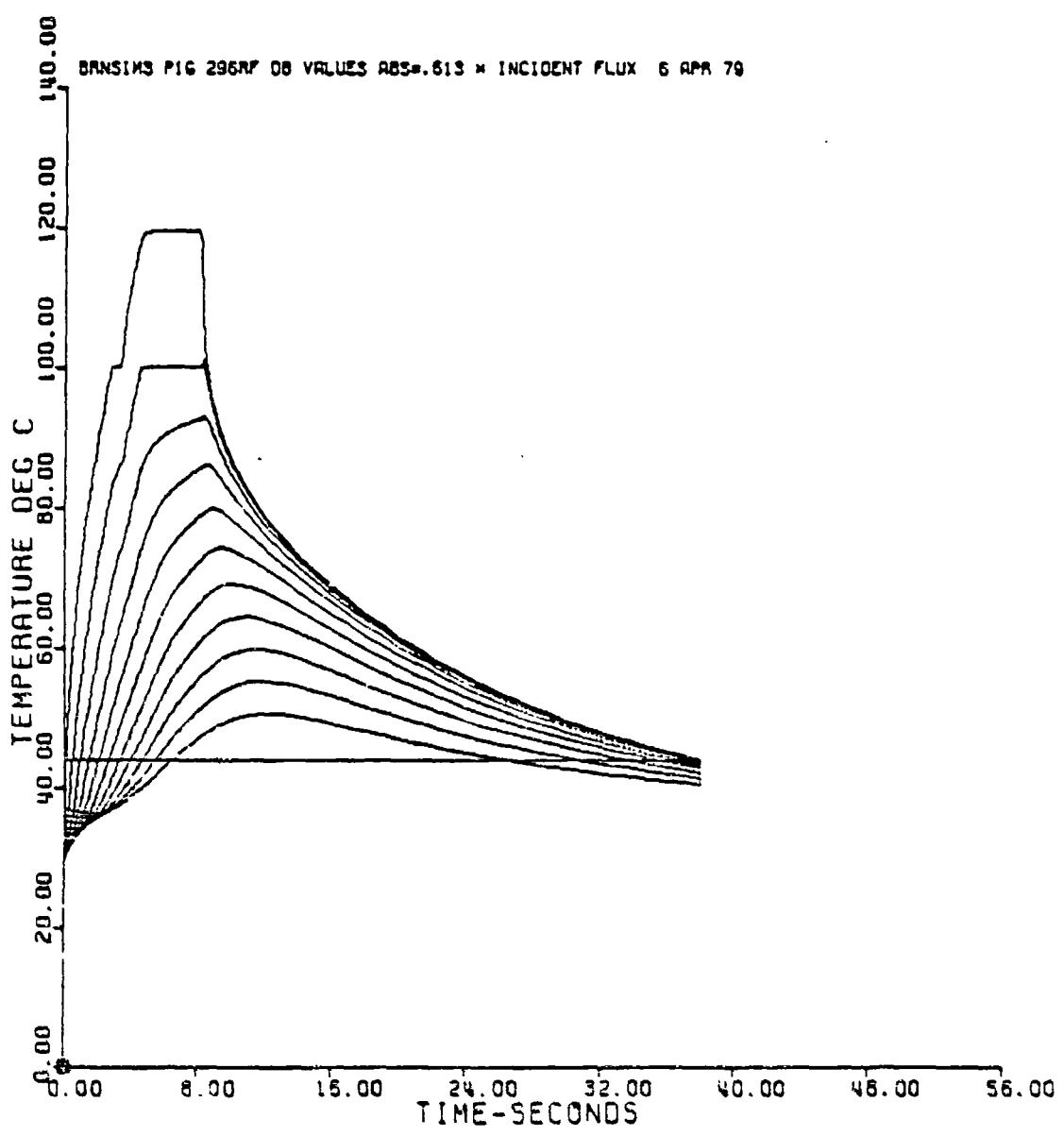


Figure 30.

TABLE VIII

Test No.	T_o	Exposure Time(S)	Fabric	Normalized Corrected	T_D^* Obs. (μm)	Model II	T_D Calc. (μm)	
					Model IIIA		Model IVA	Model IIIB
6	Sim 21208	31.8	2.97±.02	NWN	129	147	<222	99
	Sim 21213	32.2	2.97±.02	AFN	237	296	222-444	0
	Sim 31208	31.8	2.97±.02	PBI	152	201	565	54
	Sim 31213	32.2	2.97±.02	HT4	62	59	563	49
	212, 36, 11	29.8±1.2	4.97±.02	AFN	968±508	1200±529	973±541(3)	689±81
	28, 33, 39	31.3±0.8	4.97±.02	PBI	766±361	943±453	757±194(3)	761±190
	23, 27, 29, 211, 310	30.0±1.8	4.97±.02	HT4	847±633	945±650	626±144(5)	561±239
	26, 210, 37, 38, 312	29.7±1.7	4.97±.02	NWN	866±500	1043±549	756±47(5)	884±295
							799±41	1131±36

* T_D = Threshold Depth - mean ± 1 S.D. (N)

• Heat Flux, Q_s = Q absorbed by sensor with skin absorptivity = .60

** Heat Flux, Q_s = Q incident to sensory with skin absorptivity = .64

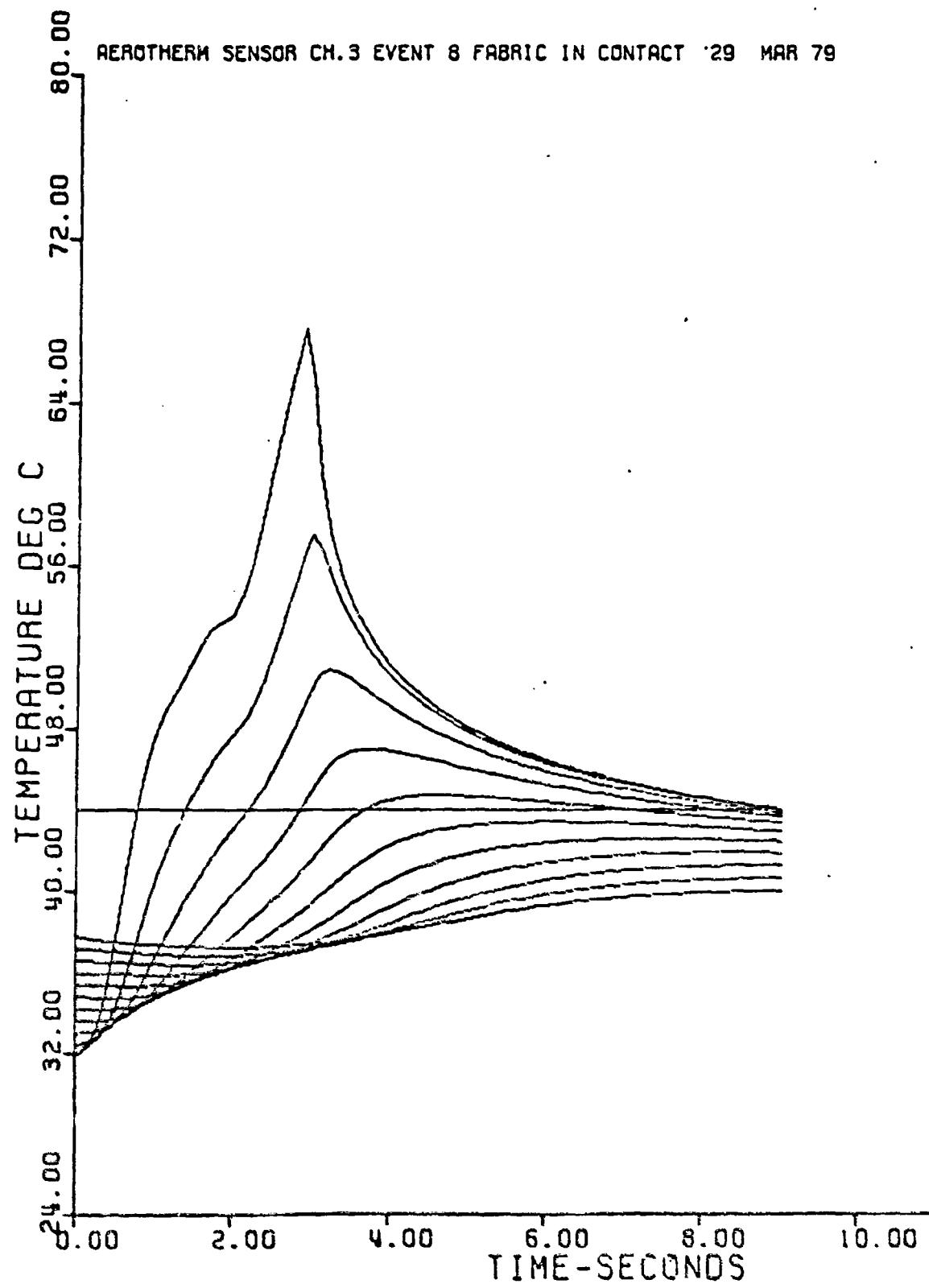


Figure 31.

different heat fluxes. The most nearly correct flux would be incident flux with an absorptivity of .613. Once again the RMS error generally favors normalized depths and would be even better with proper flux input (see Table IX).

Once again the error in shallow burn depths is pointed up. The depths for SIM31213 should be compared with the micro grades of 4 and 5 indicating from partial to complete epidermal-dermal separation. Using Table I, this would give a normalized burn depth of from 125 to 200 μm , much more in line with a Model III β prediction of 141 μm .

10.0 COMPARISON WITH WEAVER AND STOLL (7)

The results of just two simulations are presented here in Figures 32 and 33. First, Model 3 (M12VB0120) was run for Stoll's human burn data (.4 cal cm^{-2} sec $^{-1}$, Absorptivity = 0.94, ETIME = 5.6 sec and initial skin temperature of 32.5°C) using a slightly lower than normal value for blood (.0007 vs. .001) and Stoll's integration constants (PL1, PLN1, etc.). The resulting calculations for Ω at 80 μm are different by 9.4% and the total time by less than 0.4%. In Model 3 the blood cooling is turned on linearly from 0 to maximum during the first 20 seconds. There is some indication, see Figures 20, 21, and 22, that the cooling by blood does not visibly take effect until about 16 seconds after the beginning of exposure. An indication that a slightly different model, in which the blood is turned on from 37 to 45 seconds after the beginning of exposure, may be better, is shown in Figures 34 and 35. Here the predictions are different from Stoll's by 0.8% for total damage, Ω , at 80 μm and by 0.35% for total time. This is very good agreement considering the differences between the models -- Stoll: measured human skin surface temperature, no blood cooling, thermal properties constant as a function of depth, changes in conductivity as a function of time and human skin thermal properties versus Model 3: calculated pig skin surface temperature, cooling by blood, pig skin thermal properties variable as a function of depth, and initial thermal gradient.

Substitution of Takata's (15) values for the activation energy (DE) and frequency factor (PL and PLN) in the first case above results in a predicted depth of 57.1 μm compared with 105.2 μm . This indicates that different values for DE, PL and PLN should be used for the epidermal and dermal nodes. This combination of factors has not been tried.

11.0 UNANALYZED SENSOR DATA

One set of experimental data collected during the 1972/73 period remains to be analyzed. Both Aerotherm Sensors and Fabric Research Labs skin simulants were subjected to the heat from a $\frac{1}{4}$ inch thick steel plate mounted in the furnace. Unfortunately the only record of these experiments is in the form of strip chart recordings. The peak temperatures of the sensors were analyzed by KTRI (4)

TABLE IX

RMS ERROR		MODEL		
		II	III _A	III _B
#212 thru 312	Normalized	123.5	204.5	197.3
	Corrected	259.9	357.6	113.2
Sim21208 thru Sim31213	Normalized	331.0	129.3	104.8
	Corrected	313.6	167.0	127.3

MODEL NAME OR DESCRIPTION: M12W8120(120.16) STOLL'S .4CAL BLOOD=.8807 STOLL'S INT.N'G 13 MAR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP0= 32.5000
DENS= 1.00000
Q1= 0.400000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMP= 4.5000
ABSORB= 0.940000
SOIL= 100.150

PL2= 0.68
PLN2= 117.43
PL1= 0.78
PLN1= 285.52
DE2= 39109.38
DE1= 93534.58
ETIME= 5.60
ITIME= 60.00
NXTER= 8
BLOOD= 0.8807

EXTRA NODES: 30.0 40.0 60.0 80.0 100.0 130.0 160.0 190.0

FLUX FILE I.D.: 0.01 2

FLUX(1)=
1 0.400 2 0.400

W= 0.22349E+01
W= 0.52998E+00
W= 0.14571E+00

D= -0.16000E+02
D= 0.52993E+01
D= 0.59915E+01

W=1 LIES ABOVE MODE 2. INTERCOLLATING VALUES OF D AND W
COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE

W= 0.18384E+01
W= 0.94170E+00
W= 0.68745E+00

D= 0.24092E+01
D= 0.45675E+01
D= 0.50752E+01

W =	0.22340E+01	AT DEPTH (IN MICRONS)=	0.112535E-06
W =	0.18384E+01	AT DEPTH (IN MICRONS)=	20.0000
W =	0.16230E+01	AT DEPTH (IN MICRONS)=	40.0000
W =	0.13936E+01	AT DEPTH (IN MICRONS)=	60.0000
W =	0.12001E+01	AT DEPTH (IN MICRONS)=	80.0000
W =	0.10334E+01	AT DEPTH (IN MICRONS)=	100.000
W =	0.94170E+00	AT DEPTH (IN MICRONS)=	130.000
W =	0.68745E+00	AT DEPTH (IN MICRONS)=	160.000
W =	0.52998E+00	AT DEPTH (IN MICRONS)=	190.000
W =	0.33996E+00	AT DEPTH (IN MICRONS)=	200.000
W =	0.14571E+00	AT DEPTH (IN MICRONS)=	200.000
W =	0.22349E-01	AT DEPTH (IN MICRONS)=	600.000

MAXIMUM TEMPERATURE=60.857

THRESHOLD DEPTH = 100.0

FINAL TIME = 14.05

Figure 32.

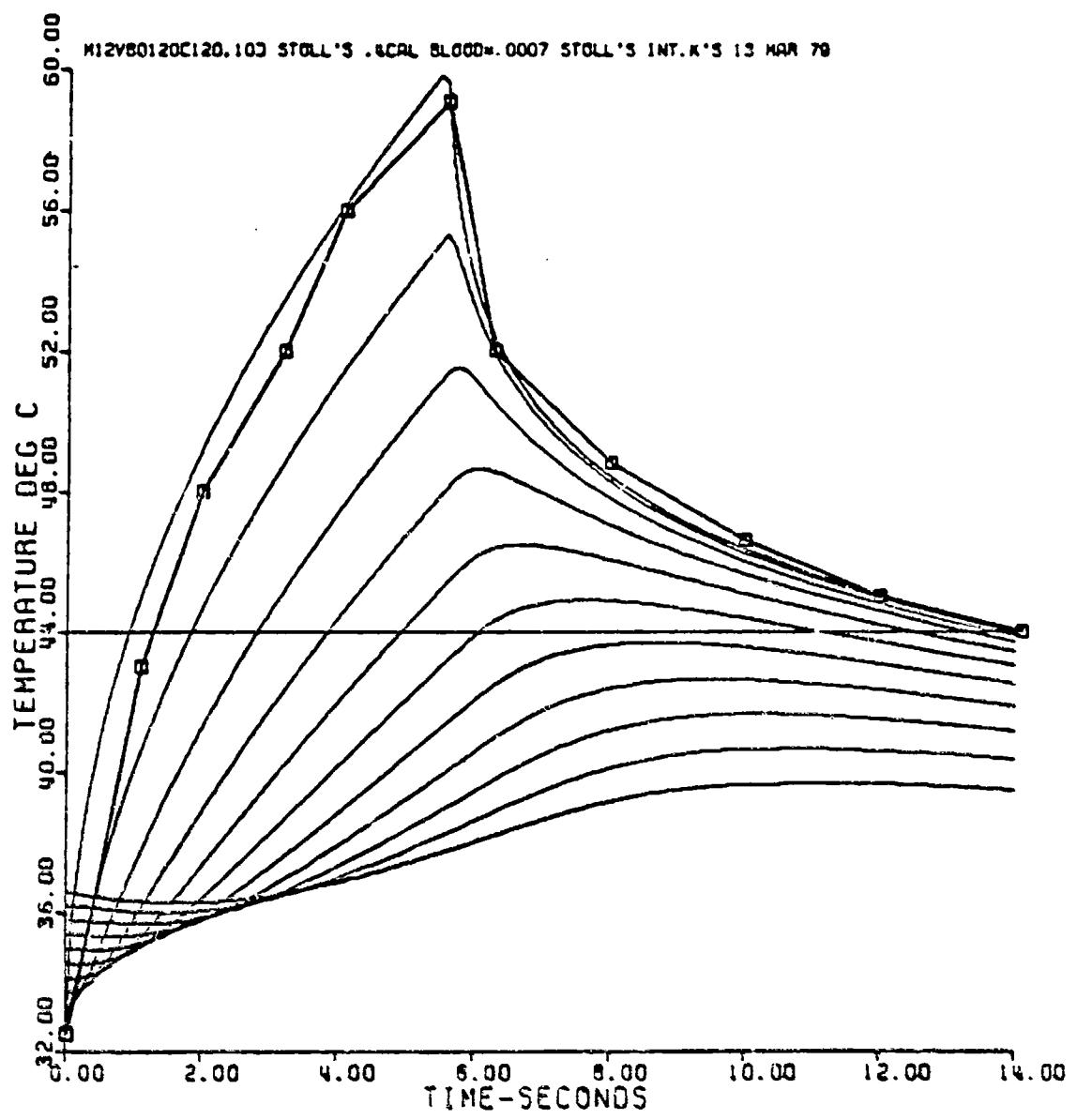


Figure 33.

FILE NAME OR DESCRIPTION: M12V337456(20.16) STOLL'S .4CAL CASE TEMPE=3.5 STOLL INTEG R 13 MAR '79

SIMULATION DATA
INPUT PARAMETER LIST

TEMP10= 32.5000
DENS= 1.00000
Q1= 0.40000
SL= 0.220000
RH= 0.100000E-01
JINC= 12
TEMPE= 3.5000
ABSORB= 0.940000
BOIL= 100.150

PL2= 0.60
PLN2= 117.43
PL1= 0.78
PLN1= 265.92
DE2= 39189.80
DE1= 93534.90
ETIME= 3.60
ITIME= 80.00
MXTRA= 8
BLOOD= 0.0010

EXTRA NOTES: 20.0 40.0 60.0 80.0 100.0 130.0 160.0 190.0

FLUX FILE I.D.: 0.01 2

FLUX(1)=
1 0.400 2 0.400

W= 0.20063E+01
W= 0.47226E+00
W= 0.12209E+00

D= -0.16000E+02
D= 0.53983E+01
D= 0.39915E+01

W=1 LIES ABOVE NODE 2. INTERCOLLATING VALUES OF D AND W
COMPUTED FROM INTERPOLATED VALUES OF P AND TEMPERATURE

W= 0.18750E+01
W= 0.33214E+00
W= 0.73456E+00

P= 0.43820E+01
P= 0.46053E+01
P= 0.48675E+01

W= 0.20063E+01 AT DEPTH (IN MICRONS)= 0.112535E-06
W= 0.17051E+01 AT DEPTH (IN MICRONS)= 20.0000
W= 0.14590E+01 AT DEPTH (IN MICRONS)= 40.0000
W= 0.12516E+01 AT DEPTH (IN MICRONS)= 60.0000
W= 0.10730E+01 AT DEPTH (IN MICRONS)= 80.0000
W= 0.93214E+00 AT DEPTH (IN MICRONS)= 100.000
W= 0.79456E+00 AT DEPTH (IN MICRONS)= 130.000
W= 0.61500E+00 AT DEPTH (IN MICRONS)= 160.000
W= 0.50400E+00 AT DEPTH (IN MICRONS)= 190.000
W= 0.47226E+00 AT DEPTH (IN MICRONS)= 200.000
W= 0.43206E+00 AT DEPTH (IN MICRONS)= 200.000
W= 0.17450E+01 AT DEPTH (IN MICRONS)= 200.000

MAXIMUM TEMPERATURE = 59.763

THRESHOLD DEPTH = 90.17

FINAL TIME = 14.00

Figure 34.

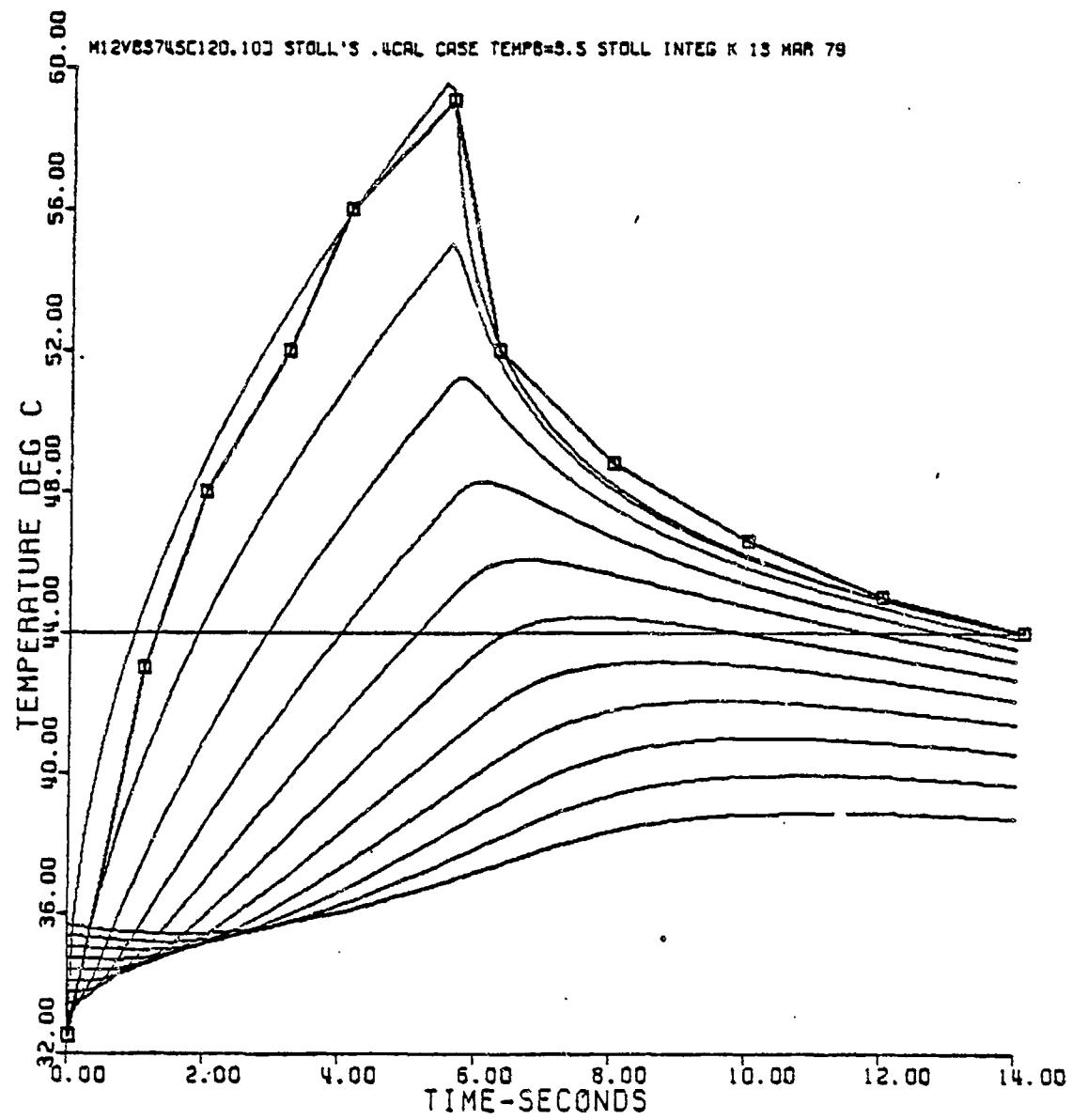


Figure 35.

to ascertain their accuracy and reproducibility. When these recordings are manually read and digitized then the voltage-time profiles can be converted to flux-time profiles and used to drive the model. It will be important to complete this analysis since some of the sensors were covered with fabric spaced $\frac{1}{4}$ " away from the surface, and represent the only such data available.

12.0 DISCUSSION

The data base has been reviewed and corrected and is now ready for release to those who wish to pursue model development on their own. As can be seen in the graphic presentations of the data, there is still a great deal of scatter which, to some extent, is unavoidable in experiments of this type. There are statistical tricks for dealing with scatter but the emphasis throughout this project has been to attempt to understand the sources of the observed variability. Uncontrolled variables such as skin temperature, time between induction of anesthesia and exposure, disagreement among pathologists regarding gradings, and unrecorded variation in shutter performance all have had an effect which cannot be removed.

An empirical, multidiscriminant model was developed to predict clinical or micro grade; but further development of it or some more appropriate model was temporarily shelved in favor of analytical model development when it was realized that the immediate need was for a model compatible with both laboratory testing and fire pit testing of thermally protective fabrics. As we better understand the relationship among total flux, exposure time and burn depth, a simplified, empirically based model may become available. For example, if, as Stoll suggested (14), plots of log exposure time versus log flux parameterized by burn grade/depth results in a family of well behaved curves or straight lines, then such plots might prove useful in screening fabrics. The first try at this approach was not entirely satisfactory. The data base and plotting routines are now available to investigate this more fully.

An analytical model was developed which takes into account tissue water boiling, a temperature gradient, a thermal properties gradient, skin absorptivity, either constant or variable (tabulated) heat flux corrected for attenuation by hair and a 10% convective component. It has been shown to predict, with reasonable accuracy, burns in pigs when they are exposed bare or protected by experimental fabrics and when the heat flux is a constant or when it is variable and derived from output of an Aerotherm sensor.

13.0 CONCLUSIONS AND RECOMMENDATIONS

1. The USAARL Porcine Burn Data Base is ready for release.
2. Data handling and graphing programs are now available which facilitate the further use and study of these data.

3. A multi-discriminant model exists which predicts clinical and micro burn grades but requires further development and study to be useful.

4. An analytical model, BRNSIM, has been developed which predicts burn depths over a wide range with reasonable accuracy.

5. It is recommended that the recently detected flaw in BRNSIM be corrected and that BRNSIM be further tested, not only with data from the USAARL data base and the University of Rochester, but also with data from the instrumented manikins as used in the Natick Fire pit.

6. It is recommended that BRNSIM be tested against the Aerotherm manikin model in its ability to predict burns over a wide range of conditions.

7. It is recommended that skin cooling by blood and tissue water boiling be further studied to clarify the dynamics of these phenomena.

8. It is recommended that BRNSIM be further tested using Stoll's extensive human burn data base.

REFERENCES

1. Knox, F. S. III et al. Thermal Analysis Program, Final Report, Vol. 1 USAARL, Ft. Rucker, Alabama, Feb. 1974. Unpublished.
2. Knox, F. S. III, G. F. McCahan, Jr. and T. L. Wachtel. Use of the Pig as a Bioassay Substrate for Evaluation of Thermal Protective Clothing and Physical Sensor Calibration. Aerospace Med. 45(8):933-938, 1974.
3. Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical Constraints on Thermal Protective Flight Clothing Design: A Bioengineering Analysis. AGARD Conference Proceedings 255(63):1-11, Dec, 1978.
4. Takata, A. N., J. Rouse and T. Stanley. Thermal Analysis Program. Report No. IITRI-J6286, U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, 36362, Contract No. DA13C01-G-0309, Feb., 1973.
5. Henriques, F. C. Studies of Thermal Injury. V. The Predictability and the Significance of Thermally Induced Rate Processes Leading to Irreversible Epidermal Injury. Archives of Path. 43:489-502, 1947.
6. Stoll, A. and L. C. Greene. Relationship between Pain and Tissue Damage Due to Thermal Radiation. J. Appl. Physiol. 14:373-382, 1959.
7. Weaver, J. A. and Stoll, A. M. Mathematical Model of Skin Exposed to Thermal Radiation. Aerospace Med. 40:24-30, 1969.
8. Mehta, A. and Wong, F. Measurement of Flammability and Burn Potential of Fabrics. Summary Report Dec. 1971-Jan. 1973. Project DSR 73884, Fuels Research Laboratory, M.I.T. Cambridge, Mass., Feb. 15, 1973.
9. Morse, H. L. et al. Analysis of the Thermal Response of Protective Fabrics. Technical Report AFML-TR-73-17, Jan. 1973. Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 45433.
10. Calvin Lum, M.D., Trip Report: Microscopic Burn Damage Data - Consultation with Dr. Walter Trevethan, NAMI, Pensacola, Nov. 27-28, 1972.
11. Hinshaw, J. R. Progressive Changes in the Depth of Burns. Arch. Surg. 87:993-997, 1963.
12. Berkley, K. M., H. E. Pearse and T. P. Davis. Studies of Flash Burns: The Influence of Skin Temperature in the Production of Cutaneous Burns in Swine. University of Rochester Atomic Energy Project UR-338, August, 1954.

13. Perkins, J. B., H. E. Pearse and H. D. Kingsley. Studies on Flash Burns: The Relation of the Time and Intensity of Applied Thermal Energy to the Severity of Burns. University of Rochester, Atomic Energy Project, UR-217, December, 1952.
14. Stoll, Alice. Comments made during Thermal Protective Clothing Ad Hoc Working Conference (Tri-Service) - U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, 3-4 April 1978.
15. Takata, A. N. Development of Criterion for Skin Burns. Aerospace Med. 45(6):634-637, 1974.
16. Lipkin, M. and Hardy, J. D. Measurement of Some Thermal Properties of Human Tissues. J. Appl. Physiol. 7(2):212-217. Sept., 1954.
17. Crank, J. and Nicholson, P. Proc. Cambridge Phil. Soc. 43:50, 1947.
18. Bruce, G. H., Peaceman, D. W., Rockford, H. H. and Rice, J. D. Trans. A.I.M.E. 198:79, 1953.
19. Knox, F. S. III, T. L. Wachtel and S. C. Knapp. Mathematical Models of Skin Burns Induced by Simulated Postcrash Fires as Aids in Thermal Protective Clothing Design and Selection. Army Science Conference Proceedings, Volume II, (AD-A056437) pp. 267-281, 20-22 June 1978, U. S. Military Academy, West Point, N. Y., also reprinted in USAARL Report No. 78-15, June, 1978.
20. Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. How to Measure the Burn-Preventive Capability of Non-flammable Textiles: A Comparison of the USAARL Porcine Bioassay Technique with Mathematical Models. Burns 5(1):19-29, Sept., 1978.
21. Cooper, T. E. and G. J. Trezek. Correlation of Thermal Properties of Some Human Tissue with Water Content. Aerospace Med. 42(1):24-27, 1971.
22. Rushmer, Robert F., Konrad J. K. Buettner, John M. Short, George F. Odland. The Skin. Science 154(3747):343-348, Oct. 1966.
23. Basar, Erol. The Circulatory Autoregulation, Chap. 4 in Biophysical and Physiological Systems Analysis, Addison-Wesley Pub. Co., Reading, Mass, 1976.

APPENDIX A

BIBLIOGRAPHY - THERMAL PROJECT

Papers:

F. S. Knox III, George D. McCahan, Jr. and Thomas L. Wachtel. Use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. *Aerospace Med.* 45(8):933-938, 1974.

Wachtel, Thomas L., Francis S. Knox III, G. R. McCahan, Jr. Methods of preparing porcine skin for bioassay of thermal injury. *Military Medicine*, July, 1977.

Knox, F. S. III, T. L. Wachtel and S. C. Knapp. Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection. *Army Scientific Conference Proceedings*, pp. 267-281, 20-22 June, 1978, Volume II, Principal Authors G thru M.

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. How to measure the burn-protective capability of nonflammable textiles: a comparison of the USAARL porcine bioassay technique with mathematical models. *Burns* (5):1:19-29, September, 1978.

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical constraints on thermal protective flight clothing design: A bioengineering analysis. *Proceedings of AGARD/NATO Aerospace Medical Panel Specialists' Meeting on Operational Helicopter Aviation Medicine*, Ft. Rucker, Alabama, 1-5 May 1978. AGARD Conference Proceedings No. 255 (63):1-11, Dec., 1978.

Abstracts:

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical constraints on thermal protective flight clothing design: A bioengineering analysis. *AGARD/NATO Aerospace Medical Panel Specialists' Meeting on Operational Helicopter Aviation Medicine*, Fort Rucker, Alabama, 1-5 May 1978.

Knox, Francis S. III, T. L. Wachtel and S. C. Knapp. How to measure the burn preventive capability of nonflammable textiles: A comparison of the USAARL porcine bioassay technique with mathematical models. *5th International Congress on Burn Injuries*, Stockholm, Sweden, 18-22 June 1978. Abstract in Abstract Book.

Reports:

Albright, J., F. Knox, D. R. DuBois and G. M. Keiser. The testing and thermal protective clothing in a reproducible fuel fire environment, phase I report: a feasibility study. March, 1971, USAARL LR 71-3-3-2.

Reports (Continued):

Knox, Francis S. III, George R. McCahan, Jr., Thomas L. Wachtel, Walter P. Trevethan, Andrew S. Martin, David R. DuBois and George M. Keiser. Engineering test of lightweight underwear of the winter flight clothing system: Thermal protection. USAARL Report #71-19. June, 1971.

Albright, John D., Francis S. Knox III, David R. DuBois and George M. Keiser. The testing of thermal protective clothing in a reproducible fuel fire environment, a feasible study. USAARL Report #71-24. June, 1971.

Knox, Francis S. Preliminary results, conclusions and recommendations from the evaluation of helmet flammability - DH-132 and T56-6 helmets. June, 1972, USAARL LR 72-17-3-5.

Knox, Francis S. III, Thomas L. Wachtel, G. R. McCahan, Jr., Calvin B. Lum, and Walter P. Trevethan. The effect of fiber and dye degradation products (FDP) on burn wound healing. USAARL-LR-73-4-1-1, Dec., 1972. Reviewed by Pruitt et al, U. S. Army Institute of Surgical Research. Ft. Sam Houston, Texas, 78234.

Knox, Francis S. and Robert W. Bailey. Results, conclusions and recommendations from the evaluation of helmet flammability - DH-132 and T56-6 helmets. May, 1973. USAARL LR 73-9-3-4.

Knox, Francis S. III and Ransom A. Nockton. Data analysis and mathematical modeling based on U. S. Army Aeromedical Research Laboratory's experimental porcine burn - Phase I data. 1 July 1975-30 September 1976. Contract DABT01-75-C-0257. LSU School of Medicine in Shreveport, Dept. of Physiology and Biophysics, Oct., 1976.

Knox, Francis S. III and Ransom A. Nockton. Data analysis and mathematical modeling based on U. S. Army Aeromedical Research Laboratory's experimental porcine burn data. Annual Summary Report, July 1977. USAMRDC Contract DAMD17-77-C-7004. LSU School of Medicine in Shreveport, Dept. of Physiology and Biophysics.

Wachtel, Thomas L., Francis S. Knox III and G. R. McCahan, Jr. A porcine bioassay method for analysis of thermally protective fabrics: a clinical grading system. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, USAARL Report No. 78-8, June, 1978.

Knox, Francis S. III, Thomas L. Wachtel and George R. McCahan, Jr. Evaluation of four thermally protective fabrics using the USAARL bioassay method. U. S. Army Aeromedical Reserach Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-9, June, 1978.

Knox, Francis S. III, Thomas L. Wachtel, George R. McCahan, Jr. and Stanley C. Knapp. The effect of fiber and dye degradation products (FDP) on burn wound healing. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-10, June, 1978.

Reports (Continued):

Knox, Francis S. III, Thomas L. Wachtel, Walter P. Trevethan and G. R. McCahan, Jr. A porcine bioassay method for analysis of thermally protective fabrics: a histological and burn depth grading system. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-11, June, 1978.

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-15, June, 1978.

Presentations:

Knox, F. S. III. Protective clothing for aviators. Presented at the Third U. S. Army Aviation Accident Prevention Conference, Fort Rucker, Alabama. 18-19 August, 1971.

Knox, F. S. III. Realistic evaluation of fabrics for thermal protective clothing. Presented to Survival and Flight Equipment Association 10th Annual Symposium, 2-5 October, 1972, Phoenix, Arizona.

Knox, Francis S. III, George R. McCahan, Jr. and Thomas L. Wachtel. The use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. Presented to Eighth Scientific Sessions of the Joint Committee on Aviation Pathology, 8-12 October, 1972. Colorado Springs, Colorado.

Knox, Francis S. III. The use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. Presented at the American Burn Association 5th Annual Meeting. 6 April, 1973, Dallas, Texas (16mm color, sound film, 20 min.).

Knox, T. (F.S. III), Stanley C. Knapp. Testing for thermal protection, an invited paper. 4th National Flame-Free Design Conference, March 11-13, 1975, San Diego, California.

Knox, Francis S. III, Stanley C. Knapp, Thomas L. Wachtel and George R. McCahan, Jr. Bioassay of thermal protection afforded by candidate flight suit fabrics. Tenth Scientific Session of the Joint Committee on Aviation Pathology, Halton, England, Sept. 6-12, 1976.

Knox, Francis S. III, Thomas L. Wachtel, George McCahan and Stanley C. Knapp. The effect of fiber and dye degradation products (FDP) on burn wound healing. Joint Committee on Aviation Pathology, Halton, England, Sept. 6-12, 1976.

Knox, F. S. III, T. L. Wachtel and S. C. Knapp. Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection. Army Scientific Conference, U. S. Military Academy, Westport, N.Y., 20-22 June, 1978.

APPENDIX B

BIBLIOGRAPHY - THERMAL ANALYSIS PROGRAM

Abstracts of Reports and Papers in Preparation:

Knox, F. S., Peter Saurmilch, S. C. Knapp, Thomas Wachtel, George McCahan and Lynn Alford. "A Fire Simulator/Shutter System for Testing Protective Fabrics and Calibrating Thermal Sensors" (USAARL Report 79-4) Ft. Rucker, Alabama: U. S. Army Aeromedical Research Laboratory, March, 1979.

The design, construction, calibration and use of a JP-4 fuel, shuttered furnace is described. Based on a NASA design this furnace simulates the radiative and convective thermal environment of a postcrash fire in rotary winged aircraft. Heat fluxes ranged from 0.5 to $3.6 \pm 3\%$ calories per square centimeter per second with steady-state furnace wall temperatures from 519°C (967°F) to 1353°C (2450°F) and a radiative/total flux ratio of approximately 0.9. A pneumatically propelled, water cooled shutter, mounted in a rolling animal carrier, controlled the exposure of pigs and thermal sensors to the fire. An electronic data acquisition and control system is also described. This system automatically controlled the opening and closing of the shutter and provided strip chart and FM magnetic tape records of exposure time, furnace wall temperature, heat flux, and sensor output. Sources of error including nonuniformity of flame front and shutter dynamics are discussed. Methods of animal handling, burn grading and photographic documentation are introduced along with a brief description of some nine experimental protocols carried out using this fire simulator shutter system.

Knox, F. S. III, Thomas L. Wachtel, S. C. Knapp. "Experimental porcine burn injury data base: listings and graphic representation."

Pigs, as human skin analogs, were exposed to simulated postcrash fires of various intensities for various durations. Some pigs were exposed bare, others with blackened skin and still others protected by thermally protective fabrics. For each exposure the location of the burn, exposure time, heat flux, initial skin temperature, date, clinical and histopathological evaluations of burn injury, corrected and normalized burn depth and a quality control number are listed. The data base contains over 45,000 items and summarizes most of the porcine burn data collected using the USAARL fire simulation furnace/shutter system. The report also includes graphic representations of items within the data base such as log exposure time versus log flux parameterized by gross grade, gross grade versus normalized burn depth, new micro grade versus normalized burn depth, gross grade versus corrected burn depth, new micro grade versus corrected burn depth, gross grade versus new micro grade, new micro grade versus total flux, gross grade versus total flux, normalized burn depth versus total flux parameterized by exposure time. These plots will show not only the relationships among various variables but also

indicate the variability seen in biological data of this kind. These data are presented for use by those who wish to continue development of mathematical models to predict burn injury.

Knox, F. S. III, Thomas L. Wachtel, George McCahan. "Thermal Properties Calculated from Measured Water Content as a Function of Depth in Porcine Skin".

In order to develop a realistic tissue water boiling routine for a mathematical model of burn development, it was necessary to know the water content of skin and the thermal properties as a function of depth. Split thickness skin samples were obtained from several pigs using an air powered dermatome. Alternate segments of these skin grafts were processed for skin water content determination and for histopathologic measurements of skin thickness. Tissue samples were weighed, dried and subsequently weighed again in a standardized protocol to determine tissue water content. In some instances the volume of tissue was also determined in order to allow the calculation of tissue density. Given a table of measured values of water content as a function of skin thickness, a least squares cubic polynomial was fit to the data and water content as a function of depth was computed from the following formula: $w(T-d) = T/d \times (W_T - W_{T-d}) + W_{T-d}$ where T is the total thickness of a slab, W_T is the fraction of water computed from the cubic equation, d is the thickness of the thin slab at a depth $T-d$, and W_{T-d} is the fraction of water above the thin slab. The thermal properties, as a function of depth, were then calculated using the formulations of Cooper and Trezek (Aerospace Med. 42(1):24-27, 1971.).

Knox, F. S. III, Nelson O'Young, Daniel D. Reneau, Chester Ellis, Thomas L. Wachtel. "BRNSIM - An Analytical Model for Predicting Thermal Cutaneous Injury". BRNSIM is a computer model written in FORTRAN IV run on a DEC PDP11/40 with 80K of core.

Since, for all practical purposes, skin is essentially opaque to thermal radiation within a postcrash fire, it can be considered to transfer energy internally by conduction only. This energy transfer in skin can be described by the heat conduction or Fourier equation. This equation was implemented in a 12 node model with appropriate boundary conditions which were initially: 1) no back radiation at the surface, 2) an adiabatic back wall, and 3) no cooling by blood. The equation set was solved by applying Crank-Nicholson method to the second order of partial derivatives and corresponding explicit methods to the first order of partials. The implicit differencing method is noted for characteristics of stability and convergence. Correct increment sizes yield reliable convergence. The model was implemented in FORTRAN using solution techniques of Thomas as described by Bruce. The initial model was subsequently revised to allow energy flux across the surface during heating, convective heat loss at the skin surface during cooling, heat transfer into deep tissues including conduction into fat and convective cooling by the blood, tissue water boiling, variable thermal properties for each node and an initial temperature profile from the surface to deep structures. The model is run interactively with

most variables changeable for each run. This model calculates in depth tissue temperatures as a function of time for each node. These temperatures are converted to a damage rate assuming first order kinetics. The damage rate is then integrated to give an indication of total damage at each node and the interpolation routine finds the depth at which the total damage, Ω , equals one. The parameters of the entire model were adjusted so that the calculated temperatures agreed with recorded intraskin temperature profiles and so that the calculated damage (threshold depth) agreed with experimental data obtained by exposing pigs, as a human skin analog, to simulated postcrash fires of various intensities. It was found that the inclusion of tissue water boiling, proper thermal properties for the skin, an initial temperature profile and heat loss to deep structures by conduction and convection were necessary to obtain calculated temperature profiles which agree with the experimentally determined profiles. It was felt that until this agreement was obtained, further adjustments in the activation energy and frequency factors of the Arrhenius relationship was an exercise in futility. The model prints a one page summary of the calculations and, at the user's option, will produce a one page plot of the calculated temperature profiles on which any experimentally determined temperature points can be overlaid. The model is designed to take heat flux as a constant value or as a table of values simulating heat flux as a function of time; thus the model can be employed using output from heat flux sensors such as those in thermoman, the U. S. Air Force/Aerotherm instrumented manikin.

Knox, F. S. III, Thomas L. Wachtel, Chester Ellis. "A Comparison of BRNSIM, a Model for Predicting Thermal Cutaneous Injury with Four Earlier Models in Their Ability to Precit Experimentally Determined Burn Injury from Three Separate Studies".

BRNSIM, a computer model described earlier, was run using activation energies and frequency factors as proposed by Moritz and Henriques, Green and Stoll, Takata, and Mehta and Wong. Experimental burn data collected by the University of Rochester study (Report No. 394), Stoll and USAARL using pigs, humans and pigs respectively were used to test the various models' ability to make accurate predictions over the entire range of burns from minor epidermal injury to complete dermal necrosis. Suggestions are made regarding the use of such models and fabric testing.

Knox, Francis S. III, Chester Ellis, Ransom Nockton. "Thermal Analysis Program: Computer Programs for Data Base Manipulation".

Twelve programs written primarily in FORTRAN IV are presented completed with source listings, comments and a brief user's manual. All of these programs have been run on a Digital Equipment Corporation PDP11/40 with 80K words of core. Programs include the following:

Program Name	Description
TAPE	Reads digitized data from tape and constructs named files for each channel of data.
MERGE	Reads data files PIG.DAT and PI.DAT on disk which have been previously read from cards and merges the two files into the data base; computes shutter corrections, normalized burn depths, group numbers, and converts temperatures to Centigrade.
SCANSEQ	Scans the sequence channel for the tapes read by program TAPE and creates a file of "events" and "cycles" for each tape to be used in locating data for a given pig.
PIGBOOK	1) Creates the pig directory PIG.DIR which locates pig data by tape, cycle number, and burn site. 2) Looks up data in the pig directory. 3) Lists the pig directory (sorted or unsorted) on the terminal or printer. 4) Edits and/or lists the event tables created by SCANSEQ. 5) Edits and/or lists the flux directory FLUX.DIR created by program FLUX. 6) Edits the data base. 7) Appends the data to the data base.
PIGWRT	Separates the digitized data for a given channel and cycle (burn) into files containing the data for a single event to be used by the data processing programs.
FLUX	Computes the flux seen by the slug calorimeter, using the files created by PIGWRT for calibration and data reduction.
TEMPFILE	Computes a temperature profile from the copper-constantan thermocouples to be used by the model program.
FURNACE	Computes the mean furnace wall temperatures seen by the Chromel-Alumel thermocouples.
PREDISC	Builds a file of values of variables selected by input to be used by the plotting program PLOTS or as input to the discriminant program.

Program Name	Description
DISCRM	Performs a linear regression analysis on data from the data base selected by program PREDISC.
PLOTS	Plots any variables in the PREDISC file vs. any other on either linear or log scales with the capability to parameterize the plot by a third variable using an input table of values and symbols.
LSTMRGD	Builds a formated file with labels of the data base to be printed by PIP (the system utility Peripheral Interchange Program).

Knox, F. S. III, and Charles Yuile. "Pitfalls in the Use of the USAARL Histopathology Grading System".

One hundred biopsy specimens from the USAARL bioassay study (USAARL Report 78-11) were reread with a view toward determining those aspects of the grading process where error and/or disagreement among the pathologists might arise. 400 biopsy specimens from the University of Rochester's studies as reported in UR Report 338 and 553 were prepared and read to ascertain whether the shrinkage seen in more severe burns in the USAARL study was also seen in the University of Rochester studies so that shrinkage correction factors could be used to make the data more consistently predictable by mathematical models such as USAARL's BRNSIM.

Takata, Arthur N., John Rouss, Thomas Stanley, F. S. Knox III, and S. C. Knapp. "Thermal Analysis Program: Thermal Studies and Mathematical Model Development in Support of USAARL Experimental Studies".

The objective of this program is to develop means for using skin simulants to assess the thermal protection afforded human beings in accidental aviation-fuel fires by various candidate fabrics. In order to achieve this objective, USAARL (U. S. Army Aeromedical Research Laboratory) has exposed pigs and skin simulants (with and without fabrics) to aviation-fuel fires burning within a specially constructed furnace. Results were then used by IITRI (IIT Research Institute) to formulate a criterion of burn depth and a code to translate simulant temperature data into burn predictions.

Other supporting endeavors of note include: a determination of the effect of pig hairs in shielding the skin from radiation; a determination of the character of the heating i.e., radiation versus convection; a determination of the water content

of pig tissue with respect to depth; and analytical studies indicating the importance of thermal properties, flux and exposure time on burns. Also computer codes have been prepared to place all experimental data on disk files for ready computer assess.

Saumilch, Peter, F. S. Knox III. "User's Manual for the Burn Prediction Computer Model Developed by NTRI."

The model described in the form of a computer program which takes the output of a physical heat flux sensor and converts that measurement of heat flux to a prediction of skin damage. Included with this report are: 1) a description of model components, (2) development of background mathematics, (3) discussion of the FORTRAN statements and (4) the User's Manual. The burn prediction model is the first in a series of models based on the data collected using the USAARL fire simulation system and the porcine bioassay technique. It incorporates tissue water boiling but does not incorporate varying thermal parameters, cooling of the skin by blood and correction for thermal shrinkage observed in the experimental data.

Wachtel, Thomas L., Edward E. Wachtel, Francis S. Knox III, and Jerry M. Shuck. "The Prevention of Thermal Cutaneous Injury by Hair".

The protective or detrimental effects of scalp and facial hair (beards and mustaches) during thermal injuries has not been determined. We have used three separate approaches to study this problem.

In a rat model, half their flank hair was alternately clipped or not clipped. Three groups of four animals were exposed to a flame heat source for one, three or ten seconds. The burns were graded clinically and histologically. Exposure versus grade curves were plotted. Hair population and density calculations were made. The protective and detrimental effects of hair were determined in a retrospective review of 407 burn victims with 154 head and facial burns. A prospective study of twenty-five human burns was undertaken to determine more accurately the protective or detrimental effects of hair on the burned skin by observation, photographic record, hair style and hair population and density determinations. The thermal input necessary for decomposition and ignition of hair samples was determined. The thermal energy deposited into the hair is represented by the formula $I = I_0 \exp^{-x/t}$

(-ax) and the formula $2\int_0^{\pi} \exp^{-(N\cdot\xi_1)\cdot\cos\theta\cdot\sin\theta} d\theta$ describes the fraction of the incident radiation that will escape interception by the hairs. From the data and these formulae the protective effect of hair was determined mathematically.

Hair cover showed significant protection to the underlying skin in the rat model in both the gross clinical grading and the histological sections throughout the entire 10 second exposure curve. In the retrospective studies the scalp was protective in all cases except in the most severe incinerations. The scalp hair and facial hair were especially protective in flash exposures. The prospective study showed beards,

mustaches, sideburns and scalp hair cover to be protective of the underlying skin in contrast to adjacent nude areas in all cases. Hair populations and density determinations varied widely, but theoretically and clinically hair protects the individual from burns.

APPENDIX C

BRNSIM 3 - LISTING OF THE INTERACTIVE ANALYTICAL MODEL BRNSIM

INPUTS:

TEMPI₀ = Initial Surface Temp. °C
Density = Density of skin = 1.0
Q_I = Incident Heat Flux either constant or as a File of Fluxes
BL = Internode depth = 220μ
AK = Calculation interval nominally .01 sec.
JINC = Nodes nominally 12
TEMPB = Differences between TEMPI₀ and backwall (fat/core) Temp. °C
Absorb = Absorptivity usually .613
Boil = Temperature when boiling occurs = 100.15 temperature °C
ETIME = Exposure Time in seconds
ITIME = Maximum calculation time usually 80-100 sec.
Nxtra = Number of extra nodes between the surface and node 1 at 220μm
Blood = Factor to adjust amount of cooling by blood usually set at .001
DE₁ & DE₂ = ΔE/R from the Arrehemius relationship for tissue temperatures from 44 to 50°C or over 50°C respectively
PL₁, PLN, or PL₂ and PLN₂ = log P = log N + ylog10
= PL + PLN
again for temperatures from 44°C-50°C or over 50°C
Cp(J) = Heat capacity as a function of depth

OUTPUTS:

INPUTS

TITLE

Flux File I.D., if used

Flux (I) - tabulated Heat flux as a function of time

DAMAGE, W, at each Depth (Node)

Maximum Temperature

Threshold Depth in μm

Final Time - total calculation time

File of calculated temperatures for later plotting by TCPLOT

File summarizing simulation

File of temperature as printed each second on the terminal

FORTRAN IV UIC-03D
CORE=13K. UIC=[120.7]

FRI 20-APR-79 10:20:33 PAGE 001
MODEL3, MODEL3=MODEL3.FTN;3

C
C
C 12-POINT BURN PREDICTION MODEL
C
C PROGRAM PIGBRN ! BURN PREDICTION MODEL WITH WATER BOILING
C ! AND USE OF EITHER CONSTANT OR TABULATED FLUX
C ! AND VARIABLE COOLING BY BLOOD FROM NODES 2 AND
C ! 3 BEGINNING AT .01 SEC AND LINEARLY INCREASING
C ! TO 20 SEC AND THEN REMAINGING CONSTANT
C.....
C
C THIS MODEL WAS DEVELOPED UNDER CONTRACT FOR THE U.S.ARMY
C MEDICAL RESEARCH AND DEVELOPMENT COMMAND, AND THE U.S.ARMY
C AEROMEDICAL RESEARCH LABORATORY, FORT RUCKER AL. 36362,
C STANLEY C. KNAPP, COL. MC. COMMANDING, BY FRANCIS S. KNOX, III, PH.D.
C WITH THE ASSISTANCE OF DANIEL D. RENEAU, PH.D., NELSON O'YOUNG,
C AND CHET ELLIS,M.S.
C
C QUESTIONS AND COMMENTS SHOULD BE ADDRESSED TO:
C
C FRANCIS S. KNOX, III, PH.D.
C ASSOC. PROF.
C DEPT. OF PHYSIOLOGY AND BIOPHYSICS
C LSU MEDICAL CENTER SCHOOL OF MEDICINE IN SHREVEPORT
C BOX 33932
C SHREVEPORT, LA. 71130
C (318)226-3134
C.....
0001 REAL*4 NOFIL, ITIME
0002 INTEGER BB
0003 LOGICAL*I RESP, YES
C.....
0004 DIMENSION T(12), F(12), G(12), H(12), Z(12), U(12), W(12)
0005 DIMENSION SV(12), CP(12,2), BK(12,2), D(12), DSCRPT(20)
0006 DIMENSION ID(4), FILNAM(5), FLUX(150), SUM(12), DW(12)
0007 DIMENSION IFLAG(12), Q(12), XTIME(12), ZTIME(12), JFLAG(12)
0008 DIMENSION WATER(12,2), DP(12, 12), THCON(2), ROCON(2), CPCON(2)
0009 DIMENSION XW(8), XTRA(8), XTRALG(8), XTMP(8), XDW(8)
C.....
0010 EQUIVALENCE (NOFIL, IBLNK)
C
0011 DATA YES/'Y'/, NOFIL/' '/
0012 DATA MAXDIM/12/, D2/200./
0013 DATA THCON/1.084316E-3, 4.1568401E-4/
0014 DATA ROCON/6.1827743E-2, .93817226/
0015 DATA CPCON/.595, .405/
C.....
C LOGICAL UNIT 1 INPUT : 'RENEAU12.DAT'; TABLES
C LOGICAL UNIT 1 SCRATCH: 'XKRCH.TMP'; VALUES OF XDW (IF COMPUTED)
C LOGICAL UNIT 2 SCRATCH: 'SCRCH.TMP'; VALUES OF DW (COMPUTED)
C LOGICAL UNIT 3 OUTPUT : 'PIGOIL.DAT'; TEMPERATURE PROFILES
C LOGICAL UNIT 4 INPUT : FILNAM; NAME OF FLUX FILE
C LOGICAL UNIT 4 OUTPUT : 'PIGOIL.PLT'; DATA FOR PLOTTING TEMPERATURE
C PROFILES
C LOGICAL UNIT 7 OUTPUT : DEFAULT 'FOR007.DAT'; SUMMARY PRINTOUT
C.....

FORTRAN IV V01C-03D
CORE=13K. UIC=[120,7]

FRI 20-APR-79 10:20:33
MODEL3, MODEL3=MODEL3.PTN;3

PAGE 002

```
C      ARITHMETIC FUNCTIONS FOR THERMAL CONDUCTIVITY (THKON) AND
C      DENSITY*HEAT CAPACITY
C
0016    THKON(Z) = (THCON(1)*Z+THCON(2))/(ROCON(1)*Z+ROCON(2))
0017    ROCF(Z) = (CPCON(1)*Z+CPCON(2))/(ROCON(1)*Z+ROCON(2))
C
0018    CALL ASSIGN(1,'RENEAU12.DAT')
0019    CALL ASSIGN(2,'SCRCH.TMP')
0020    CALL ASSIGN(3,'PIGBOIL.DAT')
C      SET UP PARAMETERS FOR THIS RUN
C.....
0021    READ(1,901)TEMP10,DENS,Q0,BL,AK,BOIL,ABSORB
0022    901      FORMAT(7F10.5)
0023    READ(1,902)JINC,TEMPB,ITIME,ETIME,PCWATR,BLOOD
0024    902      FORMAT(1I10,7F10.5)
0025    READ(1,901)(CP(J,2),J=1,JINC)
0026    READ(1,901)(BK(J,2),J=1,JINC)
0027    READ(1,901)PL2,PLN2,PL1,PLN1,DE2,DE1
0028    READ(1,901)(WATER(I,2),I=1,JINC)
0029    CALL CLOSE(1)
0030    CALL ASSIGN(1,'XKRCH.TMP')
0031      FLUX(1) = Q0
0032      FLUX(2) = Q0
0033      NFLX = 2
0034      FILNAM(1) = NOFIL
0035      PPL1 = PL1
0036      PPLN1 = PLN1
0037      DDE1 = DE1
0038      NXTRA = 0
0039      NXTRA0 = 0
0040    700      TYPE 910
0041      TYPE 911,TEMP10,DENS,FLUX(1),BL,AK,JINC,TEMPB,ABSORB,BOIL
0042      TYPE 104,PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
0043      IF (NXTRA) TYPE 7003,(XTRA(I),I=1,NXTRA)
0044    7003      FORMAT('0EXTRA NODES:',8F6.1)
0045      4      TYPE 906
0046    906      FORMAT(1X,'CONTINUE ? Y/N',T15,$)
0047      ACCEPT 220,RESP
0048      IF (RESP.NE.YES) GO TO 290
0049
0050    5      CONTINUE
0051      TYPE 699
0052
0053    699      FORMAT('1FUNCTION *''S'/'01 - REENTER INITIAL VALUES'/
1,' 2 - CHANGE SELECTED INITIAL VALUES'/' 3 - NO CHANGES'/
2,' 4 - EXIT'//'$ENTER FUNCTION NO.:')
0054      ACCEPT 801,ANSR
0055      IANSR=ANSR
0056      TYPE 710 ,ANSR
0057    710      FORMAT('0ANSR=',F10.0)
0058      BB = 0
0059      IF (IANSR.EQ.2)BB=1
0060      GO TO (20,80,230,1111)IANSR
0061
0062    20      TYPE 800,TEMP10
0063    800      FORMAT(//' PLEASE PROVIDE THE REQUESTED VALUES:'//'
1TS,'TEMP10',G16.8,T15,$)
0064      ACCEPT 801,TEMP10
0065    801      FORMAT(F10.0)
0066      GO TO (200)BB
0067    21      TYPE 802,DENS
```

FORTRAN IV V81C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33

PAGE 003
MODEL3, MODEL3-MODEL3.FTN;3

```
0068 802 FORMAT(1T5,'DENS',G16.8,T15,$)
0069 ACCEPT 801,DENS
0070 GO TO (200)BB
0071 22 TYPE 1
0072 1 FORMAT(//'$FLUX FILE NAME (BLANK IF CONSTANT FLUX): ')
0073 ACCEPT 2,FILNAM
0074 2 FORMAT(5A4)
0075 IF (FILNAM(1).EQ.NOFIL) GO TO 799
0077 CALL ASSIGN(4,FILNAM)
0078 READ(4) ID,TDELT,NFLX
0079 TYPE 3, ID, TDELT, NFLX
0080 READ(4)(FLUX(I), I=1,NFLX)
0081 CALL CLOSE (4)
0082 GO TO (200)BB
0083 GO TO 23
0084 799 TYPE 788,FLUX(1)
0085 788 FORMAT(//'$CONSTANT Q-VALUE = ',G16.8,'NOW. IT SHOULD BE Q = ')
0086 ACCEPT 801,FLUX(1)
0087 FLUX(2)=FLUX(1)
0088 NFLX = 2
0089 DO 777 I=1,4
0090 777 ID(I) = IBLNK
0091 GO TO (200)BB
0092 23 TYPE 804,BL
0093 804 FORMAT(1T5,'BL',G16.8,T15,$)
0094 ACCEPT 801,BL
0095 GO TO (200)BB
0096 24 TYPE 805,AK
0097 805 FORMAT(1T5,'AK',G16.8,T15,$)
0098 ACCEPT 801,AK
0099 GO TO (200)BB
0100 25 TYPE 806,JINC
0101 806 FORMAT(1T5,'JINC',I10,T15,$)
0102 ACCEPT 820,JINC
0103 IF (JINC.GT.MAXDIM) JINC=MAXDIM
0105 GO TO (200)BB
0106 820 FORMAT(I10)
0107 26 TYPE 807,TEMPB
0108 807 FORMAT (1T5,'TEMPB',F10.0,T15,$)
0109 ACCEPT 801,TEMPB
0110 GO TO (200)BB
0111 27 TYPE 808,ETIME
0112 808 FORMAT(1T5,'ETIME',G16.8,T15,$)
0113 ACCEPT 801,ETIME
0114 GO TO (200)BB
0115 28 TYPE 809,PL1
0116 809 FORMAT(1T5,'PL1',G16.8,T15,$)
0117 ACCEPT 801,PL1
0118 PPL1=PL1
0119 GO TO (200)BB
0120 29 TYPE 810,PLN1
0121 810 FORMAT(1T5,'PLN1',G16.8,T15,$)
0122 ACCEPT 801,PLN1
0123 PPLN1=PLN1
0124 GO TO (200)BB
0125 30 TYPE 811,PL2
0126 811 FORMAT(1T5,'PL2',G16.8,T15,$)
0127 ACCEPT 801,PL2
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120,?]

FRI 20-APR-79 10:20:33 PAGE 004
MODEL3, MODEL3-MODEL3.FTN:3

```
0128      GO TO (200)BB
0129 31      TYPE 812,PLN2
0130 812     FORMAT(//TS,'PLN2',G16.8,T15,$)
0131      ACCEPT 801,PLN2
0132      GO TO (200)BB
0133 32      TYPE 813,DE1
0134 813     FORMAT(//TS,'DE1',G16.8,T15,$)
0135      ACCEPT 801,DE1
0136      DDE1=DE1
0137      GO TO (200)BB
0138 33      TYPE 814,DE2
0139 814     FORMAT(//TS,'DE2',G16.8,T15,$)
0140      ACCEPT 801,DE2
0141      GO TO (200)BB
0142 34      TYPE 815,ITIME
0143 815     FORMAT(//TS,'ITIME',G16.8,T15,$)
0144      ACCEPT 801,ITIME
0145      GO TO (200)BB
0146 35      TYPE 816,ABSORB
0147 816     FORMAT(//TS,'ABSORB',G16.8,T15,$)
0148      ACCEPT 801,ABSORB
0149      GO TO (200)BB
0150 36      TYPE 817,BOIL
0151 817     FORMAT(//TS,'BOIL',G16.8,T15,$)
0152      ACCEPT 801,BOIL
0153      GO TO (200)BB
0154 7100    TYPE 7005,NXTRA
0155      NXTRA0 = NXTRA
0156 7005    FORMAT(//TS,'NO. OF EXTRA NODES ',I4.2X,$)
0157      ACCEPT 7007,NXTRA
0158 7007    FORMAT(I4)
0159      IF (NXTRA.EQ.0) GO TO 7230
0160      IF (NXTRA.GT.8) NXTRA=8
0161      IF (NXTRA0) TYPE 7009,(XTRA(I),I=1,NXTRA0)
0162 7009    FORMAT('CURRENT: ',8F6.1)
0163      TYPE 7011
0164 7011    FORMAT('ENTER NEW VALUES SEPARATED BY COMMAS, OR <CR> IF PROGRAM'
0165      ' IS TO CALCULATE VALUES:')
0166      ACCEPT 7013,XTRA
0167 7013    FORMAT(8F8.1)
0168      IF (XTRA(1)) GO TO 7210
C
C NUMERATOR IN NEXT STATEMENT IS SPECIFIC FOR N-POINT MODEL
C
0169      DXTRA = D2/(NXTRA+1)
0170      DO 7200 I=1,NXTRA
0171 7200    XTRA(I) = DXTRA*I
0172      DO 7210 I=1,NXTRA
0173 7210    XTRALG(I) = ALOG(XTRA(I))
0174      CONTINUE
0175      NXTRA0 = NXTRA
0176      GO TO (200)BB
0177 37      TYPE 818,BLOOD
0178 818     FORMAT('$/BLOOD = ',F10.4,3X)
0179      ACCEPT 801,BLOOD
0180      GO TO 200
0181 80      TYPE 600
0182 600     FORMAT(//TS,'PICK A NUMBER',//T10,'1=TEMP10',T30,'8=ETIME',//)
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33 PAGE 005
MODEL3, MODEL3-MODEL3.FTN;3

```
IT10,'2=DENS',T30,'9=PL1',/T10,'3=Q1',T30,'10=PLN1',//  
IT10,'4=BL',T30,'11=PL2',/T10,'5=AK',T30,'12=PLN2',//  
IT10,'6=JINC',T30,'13=DE1',/T10,'7=TEMPB',T30,'14=DE2',//  
IT10,'15=XTIME',T30,'16=ABSORBTIVITY'/  
IT10,'17=BOIL',T30,'18=EXTRA NODES'/T10,'19=BLOOD',T30//  
0186            BB=1  
0187            ACCEPT 601, INUM  
0188 601        FORMAT(I2)  
0189            GO TO (20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36  
1,7100,37) INUM  
C  
C            ANOTHER VALUE?  
C  
0190 200        TYPE 210  
0191 210        FORMAT(/' $ANOTHER CHANGE ? TYPE Y/N' )  
0192            ACCEPT 220, RESP  
0193 220        FORMAT(A1)  
0194            IF(RESP.EQ.YES)GO TO 80  
0196            GO TO 700  
0197 230        REWIND 1  
0198            TYPE 907  
0199 907        FORMAT('ENTER MODEL NAME OR DESCRIPTION (80 CHARACTERS)' )  
0200            ACCEPT 908, DSCRPT  
0201 908        FORMAT(20A4)  
0202            WRITE(3,909)DSCRPT  
0203            WRITE(7, 909)DSCRPT  
0204 909        FORMAT(' MODEL NAME OR DESCRIPTION: ',20A4)  
C  
C            ASSIGN LOGICAL UNIT 4 FOR PLOT OUTPUT  
C  
0205            CALL ASSIGN(4,'PIGBOIL.PLT')  
0206            WRITE(4)DSCRPT  
0207            AJ=JINC  
0208            Q1 = FLUX(1)  
0209            H1=BL/(AJ-1.0)  
C  
C            INITIALIZE DEPTH NODES D(J)  
C  
0210            D(1) = -16.  
0211            DO 106 I=2,JINC  
0212            D(I) = H1*(I-1)*1.E4  
0213 106        D(I) = ALOG(D(I))  
0214            DTJ = TEMPB/(JINC-1)  
0215            DO6J=1,JINC  
0216            WATER(J,1) = WATER(J,2)  
0217            CP(J,1) = CP(J,2)  
0218            BK(J,1) = BK(J,2)  
0219            XTIME(J) = 0.  
0220            ZTIME(J) = 0.  
0221            IFLAG(J) = 0.  
0222            JFLAG(J) = 0.  
0223 6           T(J) = DTJ*(J-1)+TEMP10  
0224            WRITE(4)0.,(T(J),J=1,JINC)  
0225            WRITE(3,910)  
0226            WRITE(7, 910)  
0227 910        FORMAT(1H0,55X,'SKIN DIFFUSION DATA'/,55X,' INPUT PARAMETER LIST' /)  
0228            WRITE(3,911)TEMP10,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL  
0229            WRITE(7, 911)TEMP10,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33

PAGE 006
MODEL3, MODEL3-MODEL3.FTN;3

```
0230    911 FORMAT(1X,52X,9H TEMP10=,G14.6/54X,5HDENS=,G14.6/54X,3HQ1=,G14.6/  
154X,3HBL=,G14.6/54X,3HAK=,G14.6/54X,5HJINC=,16/54X,6HTEMPB=,F8.4/  
154X,'ABSORB=',G14.6/54X,'BOIL=',G14.6/)  
0231    WRITE(3,104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD  
0232    IF (NXTRA) WRITE(3,7003)(XTRA(I),I=1,NXTRA)  
0234    WRITE(7,104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD  
0235    IF (NXTRA) WRITE(7,7003)(XTRA(I),I=1,NXTRA)  
0237    104 FORMAT(1X,53X,'PL2=',F10.2/54X,'PLN2=',F10.2/54X,'PL1=',F10.2/  
154X,'PLN1=',F10.2/54X,'DE2=',F10.2/54X,'DE1=',F10.2/  
154X,'ETIME=',F10.2/54X,'ITIME=',F10.2/54X,'NXTRA=',14/54X  
1,'BLOOD=',F10.4)  
0238    WRITE(3,3)ID,TDELT,NFLX,(I,FLUX(I),I=1,NFLX)  
0239    WRITE(7,3)ID,TDELT,NFLX,(I,FLUX(I),I=1,NFLX)  
0240    3   FORMAT('0FLUX FILE I.D.: ',4A2,F7.2,I4://' FLUX(I)='  
1/(' ',10(15,F8.3)))  
0241    JJJJ=0  
0242    F(1)=BK(2,1)/(2.0*H1*H1)-BK(1,1)/(2.0*H1*H1)  
0243    G(1)=(BK(1,1)+BK(2,1))/(2.0*H1*H1)+DENS*CP(1,1)/AK  
0244    H(1)=0.8  
0245    ITTR=0  
0246    IFLX=1  
0247    EITIM1=ITIME+1.  
0248    IF (FILNAM(1).EQ.NOFL) TDELT=AK  
0250    FFDG=TDELT/AK  
0251    KFDG=FFDG+.0001  
0252    TMPMAX=0.  
0253    QCONST=ABSORB*60.892  
0254    BLUD=0.  
0255    M=-1  
0256    TIME=0.  
0257    ITFLG=0  
0258    GO TO 12  
C  
C STATEMENT 11 AUTOMATICALLY CHOOSES PROPER INTERVAL IN FLUX TABLE  
C FOR COMPUTATION OF QT AND Q1 FOR EITHER CONSTANT OR VARIABLE  
C FLUX.  
C  
C KFDG (=FFDG) = 1 FOR CONSTANT FLUX  
C = [RATIO] OF TABULAR TIME STEP TO MODEL TIME STEP FOR  
C TABULATED FLUX  
C [...] MEANS INTEGER VALUE OF....  
C  
0259    11  IF (MOD(ITTR,KFDG).EQ.0.AND.IFLX.LT.NFLX) IFLX=IFLX+1  
0260    ITTR=ITTR+1  
0261    P=(ITTR-KFDG*(IFLX-2))/FFDG  
0262    QT=(1.-P)*FLUX(IFLX-1)+P*FLUX(IFLX)  
0263    Q1=QT*QCONST  
0264    JJJJ=JJJJ+1  
0265    TIME=JJJJ*AK  
0266    IF (TIME.GE..01.AND.TIME.LE.20.) BLUD=(TIME-.01)/19.99*BLOOD  
C  
C VALUE 23.9 IS QUESTIONABLE SHOULD BE STUDIED (RESOLVED)  
C  
0269    IF(TIME.GE.ETIME) Q1=-5.E-4*(T(1)-23.9)  
0270    Z(1)=F(1)*T(2)-((BK(1,1)+BK(2,1))/(2.0*H1*H1)-(DENS*CP(1,1))/AK)  
0271    1*T(1)+Q1  
0272    N=JINC-1  
0273    DO10J=2,N
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33 PAGE 007
MODEL3, MODEL3-MODEL3.FTN:3

```
0274      F(J) = -BK(J+1,1)/(2.0*H1*H1)
0275      G(J) = (BK(J,1)+BK(J+1,1))/(2.0*H1*H1)+DENS*CP(J,1)/AK
0276      H(J) = -BK(J,1)/(2.0*H1*H1)
0277      Z(J) = -F(J)*T(J+1)-((BK(J,1)+BK(J+1,1))/(2.*H1*H1)-DENS*CP(J,1))
0278      1/AK)*T(J)-H(J)*T(J-1)
0279      IF (J .GT. 3) GO TO 10
0280      Z(J) = Z(J)-1.675*H1/BK(J,1)*BLUD*(T(J)-TEMP10+TEMPB)
0281      10  CONTINUE
0282      F(JINC)=0.0
0283      G(JINC)=(BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)+DENS*CP(JINC,1)/AK
0284      H(JINC)=-(BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)
0285      DT=T(JINC-1)-(TEMP10+TEMPB)
0286      Z(JINC)=(H(JINC)+(DENS*CP(JINC,1)/AK))*T(JINC)
0287      1-H(JINC)*T(JINC-1)-BK(JINC,1)*DT/H1**2
0288      W(1)=G(1)
0289      U(1)=Z(1)/W(1)
0290      DO40J=2,JINC
0291      JM1=J-1
0292      SV(JM1)=F(JM1)/W(JM1)
0293      40  W(J)=G(J)-H(J)*SV(JM1)
0294      U(J)=(Z(J)-H(J)*U(JM1))/W(J)
0295      T(JINC)=U(JINC)
0296      KK=JINC-1
0297      D050J=1,KK
0298      KMJ=JINC-J
0299      IF (IFLAG(KMJ).EQ.1) GO TO 203
0300      T(KMJ)=U(KMJ)-SV(KMJ)*T(KMJ+1)
0301      IF (JFLAG(KMJ).EQ.1) GO TO 50
0302      IF (T(KMJ).LT.BOIL) GO TO 50
0303      T(KMJ)=BOIL
0304      IF (KMJ.EQ.1) GO TO 109
0305      Q(KMJ)=BK(KMJ,1)*(T(KMJ)-T(KMJ+1))/H1
0306      GO TO 205
0307      109
0308      Q(KMJ)=QT
0309      205  XTIME(KMJ)=539.*H1/Q(KMJ)*WATER(KMJ,1)
0310      ZTIME(KMJ)=XTIME(KMJ)+TIME
0311      IFLAG(KMJ)=1
0312      GO TO 50
0313      203  IF (TIME.LT.ZTIME(KMJ)) GO TO 50
0314      WATER(KMJ,1)=PCWATR
0315      CP(KMJ,1)=ROCP(WATER(KMJ,1))
0316      BK(KMJ,1)=THKON(WATER(KMJ,1))
0317      IFLAG(KMJ)=0
0318      XTIME(KMJ)=0.
0319      JFLAG(KMJ)=1
0320      CONTINUE
0321      C
0322      C INTERPOLATE EXTRA TEMPERATURES BETWEEN SURFACE AND 2ND NODE IF CALLED FOR
0323      C
0324      IF (NXTRA.EQ.0) GO TO 7360
0325      IF (T(2).NE.T(1)) GO TO 7320
0326      C
0327      C CONSTANT TEMPERATURE
0328      C
0329      DO 7310 I=1,NXTRA
0330      7310 XTMPI(I)=T(2)
0331      GO TO 7360
0332      7320 IF (T(2).NE.T(3))GO TO 7340
```

FORTRAN IV V81C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33

PAGE 008
MODEL3, MODEL3-MODEL3.FTN:3

```
C
C LINEAR INTERPOLATION
C
0333 DO 7330 I=1,NXTRA
0334 P = XTRA(I)/D2
0335 7330 XTMP(I) = (1.-P)*T(1)+P*T(2)
0336 GO TO 7360
C
C 3-POINT LAGRANGE INTERPOLATION FOR EQUALLY SPACED ABSCISSAE
C
0337 7340 DO 7350 I=1,NXTRA
0338 P = (XTRA(I)-D2)/D2
0339 7350 XTMP(I) = .5*P*(P-1.)*T(1)+(1.-P**2)*T(2)+.5*P*(P+1.)*T(3)
0340 7360 CONTINUE
0341 IF (ABS(ETIME-TIME).GT..5*AK) GO TO 48
0343 DO 44 I=1,JINC
0344 IF (IFLAG(I).EQ.0) GO TO 44
0345 WATER(I,1) = (ZTIME(I)-TIME)/XTIME(I)*(WATER(I,1)-PCWATR)+PCWATR
0347 CP(I,1) = ROCP(WATER(I,1))
0348 BK(I,1) = THKON(WATER(I,1))
0349 44 CONTINUE
0350 DO 45 I=1,JINC
0351 XTIME(I) = 0.
0352 IFLAG(I) = 0
0353 45 JFLAG(I) = 1
0354 48 CONTINUE
0355 IF (T(1).GT.TMPMAX) TMPMAX=T(1)
0357 ITFLG = -1 !ITFLG SET TO 0 IF ANY TEMPERATURE .GE. 44 DEGREES
0358 DO 13 J=1,JINC
0359 IF (T(J).GE.44.) GO TO 14
0361 DW(J) = 0.
0362 GO TO 13
0363 14 CONTINUE
0364 ITFLG = 0
0365 IF(T(J).GE.50.) GO TO 51
0367 PL1 = PPL1
0368 PLN1 = PPLN1
0369 DE1 = DDE1
0370 GO TO 15
0371 51 PL1=PL2
0372 PLN1=PLN2
0373 DE1=DE2
0374 15 DWLN=PL1+PLN1-DE1/(T(J)+273.)
0375 DW(J) = EXP(DWLN)
0376 13 CONTINUE
0377 WRITE(2)DW
0378 IF (NXTRA.EQ.0) GO TO 7400
0379 DO 7395 J=1,NXTRA
0380 IF (XTMP(J).GE.44.) GO TO 7370
0381 XDW(J) = 0.
0382 GO TO 7395
0383 7370 IF (XTMP(J).GE.50.) GO TO 7380
0384 PL1 = PPL1
0385 PLN1 = PPLN1
0386 DE1 = DDE1
0387 GO TO 7390
0388 7380 PL1 = PL2
0389 PLN1 = PLN2
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120.7]

FRI 20-APR-79 10:20:33

PAGE 009
MODEL3, MODEL3-MODEL3.FTN:3

```
0393      DE1 = DE2
0394 7390 DWLN = PL1+PLN1-DE1/(XTMP(J)+273.)
0395 XDW(J) = EXP(DWLN)
0396 7395 CONTINUE
0397      WRITE(1) XDW
0398 7400 CONTINUE
0399      EMTIME = AINT(1000.*((TIME+.00001))/100.
0400      IF ((TIME.LT.10..AND.AMOD(EMTIME,1.).EQ.0..OR.TIME.GE.10..AND.
1 AMOD(EMTIME,10.).EQ.0.) WRITE(4) TIME,T
0402      IF (ITFLG.AND.TIME.GE.ETIME) GO TO 12
0404      IF (JJJJ.EQ.M*100.OR.JJJJ.EQ.1) GO TO 12
0406      GO TO 11
0407      12 WRITE(3,840) TIME
0408      TYPE 840, TIME, (T(I), XTIME(I), I=1,JINC)
0409 840 FORMAT('0',45X,5HTIME',F10.6:,T4,'T=' ,6X,'XTIME' /(' ',2G12.4))
0410      WRITE(3,842)(XTIME(I), I=1,JINC)
0411 842 FORMAT(2X,'XTIME' ,F10.5)
0412      WRITE(3,914) T(1), CP(1,1), BK(1,1)
0413      IF (NXTRA.EQ.0) GO TO 7420
0414      DO 7410 J=1,NXTRA
0415      7410 WRITE(3,914) XTMP(J)
0416      7420 WRITE(3,914)(T(J), CP(J,1), BK(J,1), J=2,JINC)
0417      914 FORMAT(2X,'T=' ,G16.5:,2X,'CP=' ,G16.5,2X,'BK=' ,G16.5)
0418      M=M+1
0419      EM = M
0420      IF (TIME.GE.ITIME.OR.ITFLG.AND.TIME.GE.ETIME) GO TO 100
0421      GO TO 11
0422 100      CONTINUE
0423      REWIND 2
0424      READ(2) DW
0425      DO 17 I=1,JINC
0426      17 SUM(I) = .5*DW(I)
0427      DO 16 J=2,JJJJ-1
0428      16 READ(2) DW
0429      DO 16 I=1,JINC
0430      16 SUM(I)=SUM(I)+DW(I)
0431      READ(2) DW
0432      DO 88 I=1,JINC
0433      88 W(I) = (SUM(I)+.5*DW(I))*AK
0434      READ(2) DW
0435      88 REWIND 2
0436      IF (NXTRA.EQ.0) GO TO 7460
0437      REWIND 1
0438      READ(1) XDW
0439      7430 DO 7430 J=1,NXTRA
0440      7430 SUM(J) = .5*DW(J)
0441      7430 DO 7440 I=2,JJJJ-1
0442      7440 READ(1) XDW
0443      7440 DO 7440 J=1,NXTRA
0444      7440 SUM(J) = SUM(J)+XDW(J)
0445      7440 READ(1) XDW
0446      7440 DO 7450 J=1,NXTRA
0447      7450 XW(J) = (SUM(J)+.5*XDW(J))*AK
0448      7450 REWIND 1
0449      7460 CONTINUE
0450      C
0451      C      SELECT W(J) AND D(J) NEAR W(J) =1
0452      NN = 3
0453      DO 110 J=1,JINC
```

FORTRAN IV V01C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:20:33

PAGE 010
MODEL3,MODEL3-MODEL3.FTN:3

0454 JLT1 = J
0455 IF(W(J).GT.1.)GO TO 110
0457 IF(W(J).EQ.1.)GO TO 111
0459 IF (J.EQ.1) JLT1=2
0461 IF (J.EQ.JINC) JLT1=JINC-1
0463 GO TO 112
0464 110 CONTINUE
0465 JLT1 = JINC ! EXTRAPOLATE
0466 NN = 2
0467 112 WRITE(3,120)(W(K),K=JLT1-1,JLT1+1)
0468 WRITE(7,120)(W(K),K=JLT1-1,JLT1+1)
0469 120 FORMAT(1X,'W',E20.5)
0470 WRITE(3,121)(D(K),K=JLT1-1,JLT1+1)
0471 WRITE(7,121)(D(K),K=JLT1-1,JLT1+1)
0472 121 FORMAT(1X,'D',E20.5)
0473 IF (NXTRA0.EQ.0.OR.JLT1.GT.2) GO TO 1005
0475 TYPE 7015
0476 7015 FORMAT('0W-1 LIES ABOVE NODE 2. INTERCOLLATING VALUES OF D AND W/'
1.' COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE')
0477 WRITE(3,7015)
0478 WRITE(7,7015)
0479 WRITE(1)D(1)
0480 WRITE(2)W(1)
0481 DO 7470 J=1,NXTRA
0482 WRITE(1)XTRALG(J)
0483 7470 WRITE(2)XW(J)
0484 DO 7480 J=2,JINC
0485 WRITE(1)D(J)
0486 7480 WRITE(2)W(J)
0487 REWIND 1
0488 REWIND 2.
0489 DO 7490 J=1,JINC
0490 READ(1)D(J)
0491 7490 READ(2)W(J)
0492 REWIND 1
0493 REWIND 2
0494 NXTRA0 = 0
0495 GO TO 7460
0496 1005 CONTINUE
0497 NXTRA0 = NXTRA
0498 IF (W(JLT1+1).EQ.0..AND.NN.EQ.3) NN=2
0500 CALL DEPTH(D(JLT1-1),W(JLT1-1),NN,TD,IERR)
0501 IF (IERR.EQ.0) GO TO 102
0502 TYPE 1002
0503 WRITE(3,1002)
0504 WRITE(7,1002)
0505 1002 FORMAT('ERROR IN SUBROUTINE "DEPTH". EXITING.')
0506 GO TO 290
0507 102 CONTINUE
0508 IF (NN.EQ.2.AND.JLT1.EQ.JINC) GO TO 1000
0509 GO TO 1020
0510 111 TD=EXP(D(J))
0511 999 FORMAT(1X,'THRESHOLD DEPTH = ',E20.4)
0512 1000 GO TO 1020
0513 1001 WRITE(3,1001)MAXDIM
0514 1002 WRITE(7,1001)MAXDIM
0515 1003 FORMAT(1X,'THE MODEL BLEW UP: DAMAGE > 1 AT NODE ',I2)
0516 1004 WRITE(3,1004)(W(I),I=1,JINC)

FORTRAN IV V01C-03D FRI 26-APR-79 10:20:33 PAGE 011
CORE=13K. UIC=[120.7] MODEL3,MODEL3-MODEL3.FTN:3

```
0519      WRITE(7,2010)(W(I),EXP(D(I)),I=1,JINC)
0520 101  FORMAT(/(1X,'W=',E20.5))
0521 2010  FORMAT(/(1X,'W =',E20.5,5X,'AT DEPTH (IN MICRONS) =',G20.6))
0522      WRITE(3,103) TMPMAX
0523      WRITE(7, 103) TMPMAX
0524      WRITE(3,999) TD
0525      WRITE(7,999) TD
0526      WRITE(3,1021) TIME
0527      WRITE(7,1021) TIME
0528 1021  FORMAT(/, 1X,'FINAL TIME = ',F7.2)
0529 103   FORMAT('MAXIMUM TEMPERATURE = ',F8.3)
0530      TYPE 999,TD
0531      TYPE 103,TMPMAX
0532      TYPE 1021,TIME
C
0533      CALL CLOSE (4)
C
0534 290   TYPE300
0535 300   FORMAT(/'DO YOU WANT ANOTHER RUN ? TYPE Y/N')
0536      WRITE(3,98)
0537      WRITE(7, 98)
0538 98    FORMAT('1')
0539      ACCEPT 220,RESP
0540      IF (RESP.EQ.YES) GO TO 700
0541 1111  CONTINUE
0542      IOER = 0
0543      CALL DELEET(1, IOER)
0544      CALL DELEET(2, IOER)
0545      IF (IOER) TYPE 1112
0546 1112  FORMAT('ERROR IN DELETING FILE(S) ''SCRCH.TMP'' OR'
1,' ''XXRCH.TMP'''')
0547      TYPE 99
0548 99    FORMAT('1',T20,'PRINTED OUTPUT IN FILE ''PIGOIL.DAT''//T29,
1'USE "PIP" TO PRINT')
0549      WRITE(5,1050)
0550 1050  FORMAT('0',T20,'TEMPERATURES FOR PLOT IN ''PIGOIL.PLT''//T29,
1'USE TCPLT AND THEN (7,11)RASM TO PLOT')
0551      TYPE 1051
0552 1051  FORMAT('0',T20,'SUMMARY PRINTOUT IN FILE FOR007.DAT'
1,' ',T27,'USE PIP TO PRINT')
0553      CALL EXIT
0554
0555
0556
```

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES
T	000006	REAL*4 ARRAY (12)
F	000066	REAL*4 ARRAY (12)
G	000146	REAL*4 ARRAY (12)
H	000226	REAL*4 ARRAY (12)
Z	000306	REAL*4 ARRAY (12)
U	000366	REAL*4 ARRAY (12)
W	000446	REAL*4 ARRAY (12)
S	000526	REAL*4 ARRAY (12)
CP	000606	REAL*4 ARRAY (12,2) VECTORED
BK	000746	REAL*4 ARRAY (12,2) VECTORED
D	001106	REAL*4 ARRAY (12)
DSCRPT	001166	REAL*4 ARRAY (20)
ID	001306	INTEGER*2 ARRAY (4)
FILNAM	001316	REAL*4 ARRAY (5)
FLUX	001342	REAL*4 ARRAY (150)
SUM	002472	REAL*4 ARRAY (12)
DW	002552	REAL*4 ARRAY (12)
IFLAG	002632	INTEGER*2 ARRAY (12)
Q	002662	REAL*4 ARRAY (12)
XTIME	002742	REAL*4 ARRAY (12)
ZTIME	003022	REAL*4 ARRAY (12)
JFLAG	003102	INTEGER*2 ARRAY (12)
WATER	003132	REAL*4 ARRAY (12,2) VECTORED
DP	003272	REAL*4 ARRAY (12,12) VECTORED
THCON	004372	REAL*4 ARRAY (2)
ROCON	004402	REAL*4 ARRAY (2)
CPCON	004412	REAL*4 ARRAY (2)
XW	004422	REAL*4 ARRAY (8)
XTRA	004462	REAL*4 ARRAY (8)
XTRALG	004522	REAL*4 ARRAY (8)
XIMP	004562	REAL*4 ARRAY (8)
XDW	004622	REAL*4 ARRAY (8)
NOFIL	004662	REAL*4 VARIABLE
ITIME	011534	REAL*4 VARIABLE
BB	011540	INTEGER*2 VARIABLE
RESP	011542	LOGICAL*1 VARIABLE
YES	004666	LOGICAL*1 VARIABLE
IBLNK	004662	INTEGER*2 VARIABLE
MAXDIM	004670	INTEGER*2 VARIABLE
D2	004672	REAL*4 VARIABLE
THCON	011400	REAL*4 PROCEDURE
ROCP	011362	REAL*4 PROCEDURE
ASSIGN	000000	REAL*4 PROCEDURE
TEMP10	011544	REAL*4 VARIABLE
DENS	011550	REAL*4 VARIABLE
Q0	011554	REAL*4 VARIABLE
BL	011560	REAL*4 VARIABLE
AK	011564	REAL*4 VARIABLE
BOIL	011570	REAL*4 VARIABLE
ABSORB	011574	REAL*4 VARIABLE
JINC	011600	INTEGER*2 VARIABLE
TEMPB	011602	REAL*4 VARIABLE
ETIME	011606	REAL*4 VARIABLE
PCWATR	011612	REAL*4 VARIABLE
BLOOD	011616	REAL*4 VARIABLE
J	011622	INTEGER*2 VARIABLE

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES
PL2	011624	REAL*4 VARIABLE
PLN2	011630	REAL*4 VARIABLE
PL1	011634	REAL*4 VARIABLE
PLN1	011640	REAL*4 VARIABLE
DE2	011644	REAL*4 VARIABLE
DE1	011650	REAL*4 VARIABLE
I	011654	INTEGER*2 VARIABLE
CLOSE	000000	REAL*4 PROCEDURE
NFLX	011656	INTEGER*2 VARIABLE
PPL1	011660	REAL*4 VARIABLE
PPLN1	011664	REAL*4 VARIABLE
DDE1	011670	REAL*4 VARIABLE
NXTRA	011674	INTEGER*2 VARIABLE
NXTRAB	011676	INTEGER*2 VARIABLE
ANSR	011700	REAL*4 VARIABLE
IANSR	011704	INTEGER*2 VARIABLE
TDELT	011706	REAL*4 VARIABLE
DXTRA	011712	REAL*4 VARIABLE
ALOG	000000	REAL*4 PROCEDURE
INUM	011716	INTEGER*2 VARIABLE
AJ	011720	REAL*4 VARIABLE
Q1	011724	REAL*4 VARIABLE
H1	011730	REAL*4 VARIABLE
DTJ	011734	REAL*4 VARIABLE
JJJJ	011740	INTEGER*2 VARIABLE
ITTR	011742	INTEGER*2 VARIABLE
IFLX	011744	INTEGER*2 VARIABLE
EITIM1	011746	REAL*4 VARIABLE
FFDG	011752	REAL*4 VARIABLE
KFDG	011756	INTEGER*2 VARIABLE
TMPMAX	011760	REAL*4 VARIABLE
QCONST	011764	REAL*4 VARIABLE
BLUD	011770	REAL*4 VARIABLE
M	011774	INTEGER*2 VARIABLE
TIME	011776	REAL*4 VARIABLE
ITFLG	012002	INTEGER*2 VARIABLE
MOD	000000	INTEGER*2 PROCEDURE
P	012004	REAL*4 VARIABLE
QT	012010	REAL*4 VARIABLE
N	012014	INTEGER*2 VARIABLE
DT	012016	REAL*4 VARIABLE
JM1	012022	INTEGER*2 VARIABLE
KK	012024	INTEGER*2 VARIABLE
KMJ	012026	INTEGER*2 VARIABLE
ABS	000000	REAL*4 PROCEDURE
DWLN	012030	REAL*4 VARIABLE
EXP	000000	REAL*4 PROCEDURE
EMTIME	012034	REAL*4 VARIABLE
AINT	000000	REAL*4 PROCEDURE
AMOD	000000	REAL*4 PROCEDURE
EM	012040	REAL*4 VARIABLE
NN	012044	INTEGER*2 VARIABLE
JLT1	012046	INTEGER*2 VARIABLE
K	012050	INTEGER*2 VARIABLE
DEPTN	000000	REAL*4 PROCEDURE
TD	012052	REAL*4 VARIABLE

FORTRAN IV. STORAGE MAP

NAME OFFSET ATTRIBUTES

IERR	012056	INTEGER*2	VARIABLE
IOER	012060	INTEGER*2	VARIABLE
DELEET	000000	REAL*4	PROCEDURE
EXIT	000000	REAL*4	PROCEDURE

FORTRAN IV V81C-03D
CORE=13K, UIC=[120,7]

FRI 20-APR-79 10:21:01

PAGE 001
MODEL3,MODEL3=MODEL3.FTN:3

0001 SUBROUTINE DEPTH(X,Y,N,TD,IERR)
C
C INVERSE INTERPOLATION ON TWO OR THREE POINTS TO DETERMINE
C THRESHOLD DEPTH (PREDICTED BURN DEPTH) USING EITHER
C Y OR LOG(Y)
C
0002 DIMENSION X(1),Y(1),Z(3)
C
0003 IERR = 0
0004 IF (N.LT.2) GO TO 999
0006 DO 100 I=1,N
0007 Z(I) = Y(I)
0008 Z0 = 1.
0009 IF (Z(1).EQ.0..OR.Z(2).EQ.0..) GO TO 140 !USE LOGARITHMS?
0011 IF (N.EQ.3.AND.Z(3).EQ.0..) GO TO 140
0013 IF (N.EQ.2) GO TO 140
0015 Z0 = 0. !USE LOGARITHMS
0016 DO 120 I=1,N
0017 Z(I) = ALOG(Z(I))
0018 H0 = Z(2)-Z(1)
0019 IF (H0.EQ.0..) GO TO 999
0021 IF (N.EQ.2) GO TO 160
0023 H1 = Z(3)-Z(2)
0024 IF (H1.EQ.0..) GO TO 999
0026 H2 = Z(3)-Z(1)
0027 IF (H2.EQ.0..) GO TO 999
0029 DZ3 = Z0-Z(3)
0030 DZ2 = Z0-Z(2)
0031 DZ1 = Z0-Z(1)
0032 IF (N.EQ.2) GO TO 180
0034 TD = DZ1*DZ2*X(3)/(H1*H2)-DZ1*X(2)*DZ3/(H0*H1)+X(1)*DZ2*DZ3/
 1(H0*H2)
0035 GO TO 200
0036 180 TD = (DZ1*X(2)-X(1)*DZ2)/H0
0037 200 TD = EXP(TD)
0038 RETURN
0039 999 IERR = -1
0040 RETURN
0041 END

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES
X	000014	REAL*4 PARAMETER ARRAY (1)
Y	000016	REAL*4 PARAMETER ARRAY (1)
Z	000026	REAL*4 ARRAY (3)
N	000020	INTEGER*2 PARAMETER VARIABLE
ID	000022	REAL*4 PARAMETER VARIABLE
IERR	000024	INTEGER*2 PARAMETER VARIABLE
I	000042	INTEGER*2 VARIABLE
Z0	000044	REAL*4 VARIABLE
ALOG	000000	REAL*4 PROCEDURE
H0	000050	REAL*4 VARIABLE
H1	000054	REAL*4 VARIABLE
H2	000060	REAL*4 VARIABLE
DZ3	000064	REAL*4 VARIABLE
DZ2	000070	REAL*4 VARIABLE
DZ1	000074	REAL*4 VARIABLE
EXP	000000	REAL*4 PROCEDURE

DISTRIBUTION LIST

4 Copies

HQDA (SGRD-SI)
Fort Detrick
Frederick, MD. 21701

12 Copies

Defense Technical Information Center (DTIC)
ATTN: DTIC-DDA
Cameron Station
Alexandria, Virginia 22314

1 Copy

Dean
School of Medicine
Uniformed Services University of the
Health Sciences
4301 Jones Bridge Road
Bethesda, Maryland 20014

1 Copy

Superintendent
Academy of Health Sciences, US Army
ATTN: AHS-COM
Fort Sam Houston, Texas 78234